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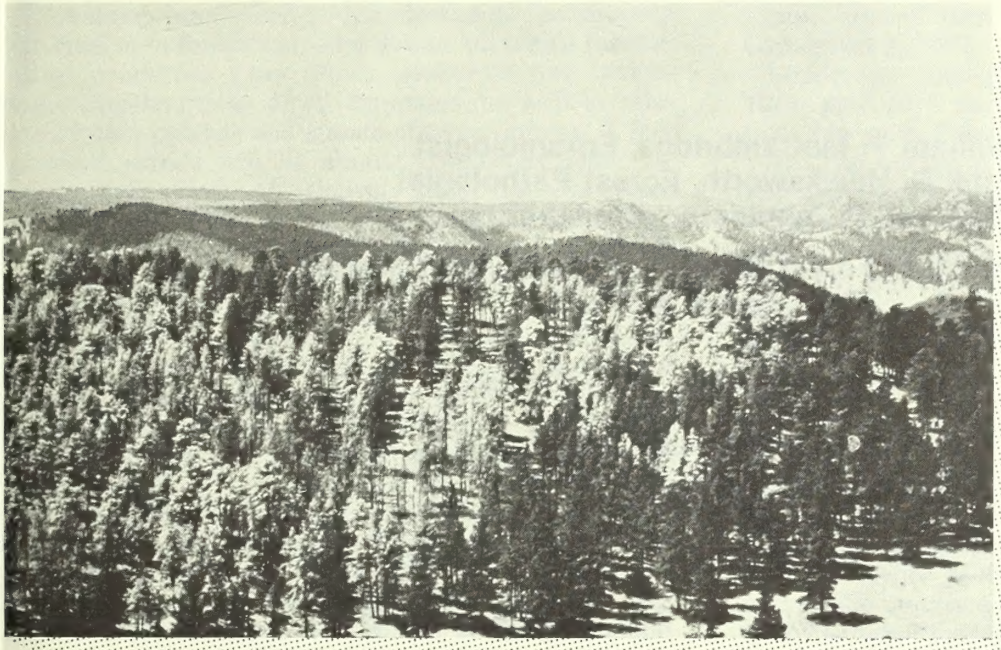
Ponderosa Pine Mortality Resulting from a Mountain Pine Beetle Outbreak

William F. McCambridge, Frank G. Hawksworth, Carleton B. Edminster and John G. Laut



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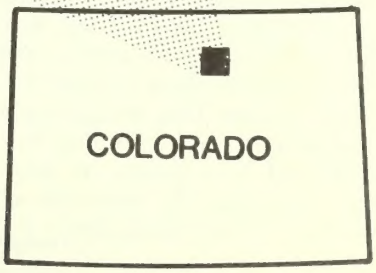

Research Paper RM-235
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

USDA Forest Service
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Ponderosa Pine Mortality Resulting from a Mountain Pine Beetle Outbreak

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Abstract

From 1965 to 1978, mountain pine beetles killed 25% of the pines taller than 4.5 feet in a study area in north-central Colorado. Average basal area was reduced from 92 to 58 square feet per acre. Mortality increased with tree diameter up to about 9 inches d.b.h. Larger trees appeared to be killed at random. Mortality was directly related to number of trees per acre and presence of dwarf mistletoe, but not to site index, elevation, or percent Douglas-fir in the stand.

[1] *Headquarters is in Fort Collins, in cooperation with Colorado State University.*
[2] *Fort Collins, Colorado.*

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Management Implications

ountain pine beetles (*Dendroctonus ponderosae* kins) in outbreak numbers do not kill whole forests. ny ponderosa pine (*Pinus ponderosa* var. *scopu-m Engelm.*) trees of all diameters, as well as rela-ly intact patches and stands of trees, survive. A few tered stands will be almost completely killed. If rstocked stands of relatively large tree diameters allowed to develop over widespread areas, control grams aimed only at treating infested trees are ound. Trees must also be thinned to some accept-e stocking level.

ilvicultural manipulation to favor nonhost trees, h as Douglas-fir (*Pseudotsuga menziesii* var. *glauca* issn.) Franco) over ponderosa pine in order to "bug of" stands, seems of little benefit in an outbreak ess one is willing to convert most of the stand to ıhost trees.

)warf-mistletoe-infected (*Arceuthobium vaginatum* ›sp. *cryptopodum* (Engelm.) Hawksw. and Wiens) ıderosa pines are more susceptible to mountain pine tle attacks than are healthy trees. Consequently, est management practices aimed at reducing stand k to bark beetles by thinning stands should simul-ıeously remove dwarf-mistletoe-infected trees.

Introduction

This paper provides some answers to the question What happens to a ponderosa pine forest during an controlled mountain pine beetle outbreak?" The jective of the paper is to present specific data on the ıount of beetle-caused tree and stand mortality. Tree ›rtality is considered in relation to tree diameter, ınd density, elevation, site index, aspect, Douglas-fir mponent, and dwarf mistletoe infection.

History of the Outbreak

Mountain pine beetles began infesting small groups ponderosa pine in Lory State Park near Fort Collins, ılo., about 1965. Beetles infested approximately 300 ;es throughout 1,220 forested acres of the park in 1967, and the rate increased to about 1,000 per year by 1968. By the end of 1973, numerous groups of 25-50 actively infested pines were distributed throughout the forest. Several thousand trees are believed to have been killed by 1973.

Maximum tree mortality occurred during 1974, 1975, and 1976 and was estimated at about 20,000 trees per year. Infested trees were noticeably fewer in 1977. The outbreak ended in 1978, when only a few, scattered trees were lightly infested.

The mountain pine beetle epidemic in the park was part of a large outbreak that extended about 180 miles from the Wyoming-Colorado border, southward to the vicinity of Canon City, Colo., and encompassed about 2,000,000 acres of ponderosa pine type.

The Study Area

Lory State Park is 7 miles west of Fort Collins, Colo. The elevation of the forest within the park extends from 5,840 to 7,015 feet. While ponderosa pine is the principal type, individual Douglas-firs are scattered in the pine stands and grow in pure stands on north-facing slopes. Pine stands on steep, south slopes consist of scattered, open grown trees.

Annual precipitation, extrapolated from Redfeather Lakes, Estes Park, and Fort Collins, is approximately 20 inches. Most of this falls as late winter and early spring snows and as summer showers.

The mean age of 509 dominant or codominant ponderosa pines was 101 ± 3 years. Pine stands in the park are generally uneven-aged, consisting of an irregular mosaic of small, even-aged patches of trees established following homestead clearings, mining, fires, and bark-beetle epidemics.

Methods

Crews conducted the survey of mountain-pine-beetle-caused damage throughout the forested area of Lory State Park in October 1978. Crews sampled 189 BAF 5 variable-radius plots, 179 of which were forested. Plot centers were on an 8-chain square grid pattern. Grid lines were closed (distance and direction to previous line measured) at each end, so actual plot locations could be determined. The elevation of each plot was then estimated from a U.S. Geological Survey contour map of the area.

At each forested plot, crews determined the aspect and recorded the following data for each tree taller than 4.5 feet: tree species, d.b.h. to the nearest 0.1 inch; life status (i.e., alive, beetle-killed, or dead from unknown causes); and the dwarf mistletoe rating (Hawksworth 1977) for live ponderosa pines, or a notation of evidence of dwarf mistletoe if the tree was dead. The height to nearest foot of two trees in each 1-inch diameter class, and the age of three dominant or codominant trees at 1 foot above mean ground line, were also determined.

The average length of time required for ponderosa pines to reach a height of 1 foot was determined by felling 112 saplings and counting annual rings at ground level and at 1 foot. The mean number of years to grow the first foot, 7 ± 1, was added to the mean age of cores taken at 1 foot for determining site index from curves using total age (Meyer 1938).

The least sampling unit used in analyzing the data was the BAF 5 variable-radius plot. Calculations of analyses of variance, Pearson coefficients of correlation, *t* tests, and multiple regressions were made as needed.

Within the forest at Lory State Park is an irregular shaped area of 163 contiguous acres of ponderosa pine which suffered heavy tree mortality from beetle attacks. This area has an elevation range of 6,720-6,960 feet. Tree mortality within the area was compared to that for the whole forest and to other plots at similar elevations where overall tree mortality was less to ascertain the tree or stand characteristics associated with very heavy beetle-caused tree mortality.

Results and Discussion: Factors Affecting Beetle-caused Tree Mortality

Mountain pine beetles killed an average of 92 ponderosa pines per acre in Lory State Park. This was 25% of the original live pines, containing 37% of the pine basal area and 44% of the merchantable board foot volume. During the outbreak, beetles killed approximately 112,500 ponderosa pines, containing a merchantable volume of 1.2 million board feet worth about $17,000.[3] Lory State Park is managed for recreation and wildlife habitat; consequently, the major direct cost of the beetle outbreak may be the money spent in the future to remove dead trees adjacent to hiking trails for safety and area accessibility.

Within the 163 contiguous acres of very heavy beetle-caused mortality, 273 trees (49% of the pine stems) were killed per acre. These pines contained 84% of the original pine basal area and represent a loss of more than 3,000 board feet per acre—99% of the original merchantable board foot volume.

Tree Diameter

The average d.b.h. (average d.b.h. is the diameter of the tree of average basal area) of all live ponderosa pine 4.5 feet tall and taller was reduced from 8.9 inches to 8.3 inches during the outbreak (table 1). Tree mortality by diameter class is shown in table 2. Mountain pine beetles killed trees down to the 1-inch

[3]Average stumpage value between 1974 and 1977 equaled $14.30 per thousand board feet. Data from Proof Listing of Timber Sale Report, USDA Forest Service, Rocky Mountain Region, Denver, Colo.

Table 1.—Comparison of characteristics of ponderosa pine forest study areas having heavy beetle-caused mortality or moderate mortality versus whole-forest characteristics[1]

Characteristic	Whole forest		Area of heavy tree kill[2]		Area of moderate and scattered mortality[2]	
	Mean	SD	Mean	SD	Mean	SD
Tree diameters	*inches*					
Pre-outbreak	[3]8.9(179)	2.7	8.0(25)	2.7	9.0(56)	2.9
Killed by beetles	10.3(127)	3.5	9.6(25)	2.5	10.2(39)	3.7
Residual	8.3(177)	3.1	5.4(24)	1.9	8.5(56)	3.1
Density	*stems per acre*					
Pre-outbreak	369	522	561	585	420	615
Killed by beetles	92	162	[4]273	284	[4]86	136
Residual	277	422	288	372	334	515
Basal area	*square feet per acre*					
Pre-outbreak	92	53	122	40	97	63
Killed by beetles	33	40	95	31	31	39
Residual	59	43	27	22	66	46

[1]Analysis includes trees 4.5 feet and taller.

[2]Altitudes of study areas are similar (6,720 to 6,960 feet); analysis includes trees 4.5 feet and taller.

[3]Number of plots used is given in parentheses after the mean value. Sample size for whole area was 179 forested plots; for area of heavy kill, 25; and for area of moderate tree kill, 56 plots. Where sample sizes in a given column are unequal, some plots did not contain characteristic measured. For example, 2 plots taken from the whole forest contained no residual trees, while 52 plots had no trees killed by beetles.

[4]Difference significant at $P < 0.001$.

Table 2.—Overall tree mortality (by diameter class) caused by mountain pine beetle, sample plots, Lory State Park, Colo., 1978

Diameter class (midpoint)	Total trees (n = 3474)		Trees killed (n = 1239)	
inches	*number*	*percent (of all trees)*	*number*	*percent*
[1]1	14	<1	0	0
3	197	6	17	9
5	389	11	73	19
7	537	15	196	36
9	610	17	265	43
11	561	16	236	42
13	506	15	220	43
15	344	9	142	41
17	167	4	51	30
19	87	2	21	24
21	34	1	11	33
23	15	<1	1	6
25	3	<1	2	66
27	3	<1	0	0
29	3	<1	2	66
31	1	<1	1	100
33	2	<1	0	0
35	1	<1	1	100

[1]*0-1.9, etc.*

diameter class. Percent of trees killed in each diameter class increased steadily up to 9 inches. The lack of a sharp demarcation in number of attacks at some smaller diameter implies that, during outbreaks, no specific minimum tree diameter exists below which trees are immune from beetle attack.

Approximately equal percentages of pines between 8 and 14 inches d.b.h. were killed. Beetle-caused tree mortality appears to lessen or become erratic for trees larger than 14 inches d.b.h. This relationship may actually exist, although the correlation coefficient for percent of trees killed versus d.b.h. (−0.04) indicates no relationship. For the largest diameters, the sample sizes are too small for inference. In any event, some large trees survived this outbreak.

The distribution of pine diameters within Lory State Park reveals a lack of small trees. For example, trees smaller than 4 inches d.b.h., but at least 4.5 feet tall, account for only 6% of the stems. On the other hand, trees from 4 to 14 inches d.b.h. account for almost 81% of the stems.

In the 163-acre area of high beetle-caused tree mortality, average d.b.h. of pines decreased significantly from 8.0 inches prior to the outbreak to 5.4 inches at its end. Prior to the outbreak, the average d.b.h. of pines in this area was 0.9 inch smaller (table 1) than the mean for pines in the whole forested area, but the difference was not significant. Average d.b.h. of 8.0 inches in the area of heavy tree mortality was not statistically different from 9.0 inches for plots at the same elevational range where tree kill was much less severe.

The percent of trees killed by beetles in the area of high tree mortality, for the most part, increased as tree diameter increased up to 12 inches (table 3). There was a drop in percent tree mortality in the 14- and 15-inch diameter classes, probably caused by chance.

A more erratic pattern of tree mortality relative to diameter is seen in table 4. This area of moderate beetle-caused damage within the same elevational range as the 163-acre area more closely resembles in tree and stand characteristics the area as a whole (table 1). The pattern of tree mortality increasing as diameter increased reveals a somewhat haphazard selection by the beetles.

The relationship between ponderosa pine tree diameter and mortality resulting from mountain pine beetle attacks at Lory State Park can be summed up as follows: (1) Tree mortality over the area did not correlate well with diameter. When this outbreak had run its course, many large trees had survived. (2) The percent of trees killed by beetles increased as diameters increased, but not indefinitely. Trees 8 or 9 inches in diameter were almost as likely to be killed as larger trees. (3) No specific d.b.h. exists below which trees escaped mountain pine beetle attacks. (4) However, the steep downturn in percent of trees killed appears to lie in the vicinity of 8-9 inches d.b.h. This is similar to data from lodgepole pine provided by Cole and Amman (1969). This diameter range may be useful for establishing a minimum diameter in managed even-aged stands where mountain pine beetles are a problem. (5) Heaviest stand destruction did not occur where mean tree diameter was greatest.

Stand Density

Stand density for trees 4.5 feet and taller can be expressed as trees per acre or basal area per acre. Of the two, original trees per acre appears to give the stronger correlation with the number of trees killed by the beetles ($r = 0.71$ versus 0.61). A multiple regression

Table 3.—Tree mortality (by diameter class) in heavy loss area, sample plots, Lory State Park, Colo., 1978

Diameter class (midpoint)	Total trees (n = 615)		Trees killed (n = 471)	
inches	*number*	*percent (of all trees)*	*number*	*percent*
[1]1	5	<1	0	0
3	31	5	2	6
5	73	12	28	38
7	103	17	71	69
9	124	20	111	90
11	111	18	100	90
13	101	16	99	99
15	50	8	44	88
17	14	2	13	93
19	3	<1	3	100

[1]*0-1.9, etc.*

analysis showed that this relationship of tree mortality was not strengthened when compared to the combined interaction of original trees per acre × original basal area ($r = 0.68$), or the interaction of original trees with d.b.h. ($r = 0.71$).

Ponderosa pine were significantly reduced from 369 to 277 trees per acre within the park ($P < 0.001$). In the area of heavy beetle-caused tree mortality, the density of pine stems, 561 per acre, was not statistically different from that for the area as a whole, 369 per acre, or for the area of moderate tree mortality at similar elevations, 420 per acre (table 1). The large standard deviations accompanying these means indicates a need for additional sampling before we could say whether the beetles did or did not prefer the more dense stand.

The basal area of ponderosa pine at Lory State Park was reduced from 92 to 58 square feet per acre (table 1). This difference is significant at $P < 0.001$. The large variations in basal area between sample plots is evident in the large standard deviations. In the area of heavy tree mortality, the basal area of pine was significantly greater than that for the entire forested area (122 versus 92 square feet per acre, $P < 0.001$), but it was not different ($P = 0.05$) from mean basal area in the areas at similar elevation containing less tree kill (97 square feet per acre).

The loss of 25% of pine stems when the accompanying basal area was 92 square feet suggests that present cutting guides calling for a residual stand of 80 basal feet may not reduce the susceptibility of stands sufficiently during outbreaks. Tree spacing and residual diameter may be additional stand characteristics worthy of consideration.

Table 4.—Tree mortality (by diameter class) in moderate loss area, sample plots, Lory State Park, Colo., 1978

Diameter class (midpoint)	Total trees (n = 1166)		Trees killed (n = 364)	
inches	*number*	*percent (of all trees)*	*number*	*percent*
– 1	*5*	<1	0	0
3	74	6	7	10
5	153	13	27	18
7	192	16	56	29
9	201	17	68	34
11	175	15	74	42
13	167	14	61	37
15	109	9	43	39
17	41	4	9	22
19	19	2	7	37
21	10	<1	5	50
23	9	<1	1	11
25	2	<1	2	50
27	4	<1	1	25
29	3	<1	2	66
31	1	<1	1	100
33	0	<1	0	0
35	1	<1	1	100

[1] *0-1.9, etc.*

Elevation

Elevation was not significantly correlated with percent of pine trees killed by beetles ($r = 0.23$); with site index ($r = 0.01$); with ponderosa pine stems per acre ($r = 0.19$); with pine basal area ($r = 0.23$); or with Douglas-fir per acre ($r = -0.03$).

Site Index and Aspect

The range of ponderosa pine site indexes was 25-82 feet, with a mean of 47.2 ± 1.94 feet. Site index had no significant influence on stand density ($r = -0.07$), basal area ($r = 0.02$), or percent of pine killed ($r = 0.14$). Mean pine site index for plots within the area of contiguous heavy tree mortality was 52.4, significantly higher ($P = 0.01$) than the 46.0 for plots within the same elevation range where beetle-caused tree mortality was less. Site index did not change with elevation or aspect.

The density of ponderosa pine trees was significantly less ($P < 0.05$) on south and east slopes than on the west aspect (table 5). But percent of trees killed by beetles was not different between aspects.

Douglas-fir

Thirty-one plots on north-facing slopes were analyzed for the influence of the Douglas-fir component on ponderosa pine mortality caused by beetles. Douglas-fir ranged from 0% to 94% of all trees, averaging $37 \pm 14\%$. No relationship was detected in a comparison of the number of Douglas-fir trees per acre with the percent of ponderosa pines killed by the mountain pine beetle, or of Douglas-fir stems, as a percent of all stems, with the percent of ponderosa pine killed by beetles. The Douglas-fir component appears to have increased following the beetle outbreak, but the difference is not statistically significant (table 5).

Amman and Baker (1972) reported that mixed stands of up to 36% trees of other species (other than lodgepole pine (*Pinus contorta* Dougl.)) were as susceptible to mountain pine beetles as those with less than 10% of other species. McGregor (1978) also reported similar results in lodgepole pine.

The data indicate that efforts to reduce pine mortality during beetle outbreaks by increasing the amount of Douglas-fir in the stand will not be effective unless something approaching a complete type conversion is effected.

Dwarf Mistletoe

The relationship between ponderosa pine dwarf mistletoe and increased susceptibility to mountain pine beetle has long been a subject of speculation. Various reports from the Colorado Front Range suggest that stands heavily infested by dwarf mistletoe are more

susceptible to the beetle (Cahill 1975, Creasap 1977, Frye and Landis 1975, Johnson et al. 1976). In the most detailed study (Johnson et al. 1976), four areas totaling 86 acres were examined in the Pike-San Isabel National Forest (three stands) and in the Arapaho-Roosevelt National Forest. In areas where dwarf mistletoe infestation was low (stand mistletoe ratings of 0.3 to 0.9), there was no relationship between dwarf mistletoe and mountain pine beetle attack. Only when dwarf mistletoe rating of the stand averaged 1.4 was there a significant trend for mountain pine beetles to infest mistletoe-infected trees.

In this study, dwarf mistletoe was found in 41 of the 179 forested plots (23%). There was a definite increase of dwarf mistletoe with elevation. No infection was found in plots under 6,000 feet, but 45% of the plots in the highest parts of the area (over 6,800 feet) had mistletoe.

For the 41 plots with mistletoe, 52.9% of the trees were infected; however, only an average of 12.1% of the trees were infected in the entire area. A greater percentage of dwarf-mistletoe-infected ponderosa pines was killed by mountain pine beetle (30.8%) than of uninfested trees (20.5%). This trend was fairly consistent in each diameter class (table 6), but the data for trees over 13 inches d.b.h. are scanty.

A stand summary of dwarf-mistletoe-infested versus uninfested plots (table 7) shows beetle-caused losses, as measured by percent of stems killed, basal area, merchantable cubic foot volume, and board foot volume, were significantly higher ($P < 0.1$ by t test) in mistletoe-infested plots. The differences in proportion of trees killed in dwarf-mistletoe-free plots (16%) versus that in infested plots (39%) is greater than for uninfected versus infected trees (table 6, 20% versus 31%). We interpret this to mean that not only are dwarf-mistletoe-infected trees more susceptible to the beetles, but adjacent, nondiseased trees are also more susceptible because of the attractive odors released by female beetles attacking the diseased trees.

The incidence of dwarf mistletoe was not influenced by number of trees per acre or tree size.

Table 6.—Relationship between mountain pine beetle kill, dwarf mistletoe infection and diameter class

Diameter class—midpoint	Mistletoe-infected trees per acre		Mistletoe-free trees per acre	
	Total	Killed	Total	Killed
inches	*number*	*percent*	*number*	*percent*
[1]1	2.9	0	57.7	13.4
3	15.8	10.6	89.3	6.8
5	9.5	25.8	62.6	16.3
7	7.2	56.3	42.3	33.1
9	3.9	66.7	31.2	40.3
11	2.6	46.2	19.0	42.7
13	2.4	66.7	11.7	39.4
15	0.8	50.0	6.3	40.6
17	0.3	33.3	2.5	32.0
19	0	0	1.0	20.0
21	0	0	0.3	33.3
Total	45.4	30.8	323.9	20.5

[1] *0-1.9, etc.*

Dwarf mistletoe was most abundant in the 163-acre area of heavy beetle damage (8 of 17 plots, compared to 33 of 162 plots in the rest of the area).

Dwarf mistletoe in the original stand, in trees ≥6 inches d.b.h., was found overwhelmingly on west aspects, where 48.7% of the stems were infected. Pines on south aspects had an 8.4% infection; east, 7.9%, while 2.1% on north aspects were infected. Such large differences have not been recorded in other studies for this mistletoe in the southwest (Hawksworth 1959, Andrews and Daniels 1960).

Summary

An uncontrolled mountain pine beetle outbreak ran its course during a 14-year period in the ponderosa pine forest of Lory State Park, 7 miles west of Fort Collins, Colo. These findings are generalizable to the ex-

Table 5.—Aspect, site class, and Douglas-fir component as related to mountain pine beetle impact on ponderosa pine

Aspect[1]	Number of plots[2]	Site index		Original ponderosa pine stems per acre	Ponderosa pine mortality	Douglas-fir stems[3]		
		Ponderosa pine	Douglas-fir			Original	Post-outbreak	Differences[3]
						percent		
North	31	46	64	452	26.2	37.5	44.4	NS
East	22	50	60	161	27.6	21.6	27.6	NS
South	17	45	--	155	18.0	1	1	
West	8	46	--	730	23.1	1	1	

[1] *Cardinal directions ± 20°.*

[2] *Plots on level ground, or those on aspects other than the cardinal directions are not represented. Hence the total of 78 plots out of 179.*

[3] *Significance of differences between North and East determined by t test with arcsin transformation.*

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Table 7.—Comparision of ponderosa pine in plots with and without dwarf mistletoe, after mountain pine beetle attack

Stand condition	number of plots	Percent loss to mountain pine beetle			
		Number of stems	Basal area	Merchantable cubic feet	Board feet
		mean ± SE			
Mistletoe-free	138	16 ± 1	28 ± 3	32 ± 3	33 ± 3
With mistletoe	41	39 ± 5	46 ± 5	50 ± 5	53 ± 6
Significance level		0.01	0.01	0.01	0.01

tent the situation described might be considered a microcosm of the ponderosa pine type of the Roosevelt National Forest and adjacent private lands.

The mountain pine beetle killed 25% of the ponderosa pine trees 4.5 feet and taller, or 92 trees per acre, over the entire 1,220 forested acres in the park. Merchantable wood volume loss was about 960 board feet per acre.

Much heavier tree mortality occurred in scattered locations. In one area of 163 acres, 49% of all ponderosa pine trees taller than 4.5 feet were killed by beetles. This represented a loss of about 3,000 board feet (99%) of the merchantable volume per acre. Basal area and site index were significantly higher in the area of highest tree mortality, but mean tree diameter was lower. Density of trees looked considerably higher but failed to be statistically different from the other areas. This variable should be studied further before the statistical evidence is accepted. A high proportion of tree loss in the area of heavy, contiguous, beetle-caused tree mortality was on the leeward side of ridges. This facet of beetle-host relationship also warrants further study.

Percent of pines killed increased steadily with tree diameter up to about 9 inches. Beyond that diameter, tree mortality remained high but appeared random, especially in the largest diameter classes. All trees in some diameter classes were killed, but some big trees survived. However, mean tree diameter was lowered as a result of the beetle outbreak.

There was no tree diameter evident below which ponderosa pine is immune from beetle attack during an outbreak.

The original density of ponderosa pine correlated fairly well with trees killed by beetles, $r = 0.71$, but not with percent of pine killed, $r = -0.001$. Interaction of tree density with tree diameter did not materially strengthen the correlation. Original basal area of pine was less well correlated with pine trees killed, $r = 0.61$. The correlation with percent of trees killed was $r = 0.15$.

Elevation, site index, aspect, or amount of Douglas-fir mixture with pine had no measurable influence on the amount of pine mortality caused by mountain pine beetles in this outbreak.

A greater percent of dwarf-mistletoe-infected trees was killed than those free of infection. Infection was fairly uniform between diameter classes. However, greatest percent of beetle-caused mortality occurred in trees from 12 to 13.9 inches d.b.h. This may be more diameter-related than due to dwarf mistletoe. Influence of the intensity of infection and beetle susceptibility could not be determined by this study. Adequate numbers of dwarf-mistletoe-infected trees of all diameters remain in the residual stand to maintain the disease.

The magnitude of mountain-pine-beetle-caused forest destruction reported here may help one more realistically evaluate the need for direct chemical control programs. Certainly all trees are not destroyed. A program of stand thinning, coupled with use of the highly effective and economical protective sprays of carbaryl (McCambridge 1981), supplemented by judicious direct control as outlined by Stevens et al. (1975), would enable private landowners to do much to limit tree losses, even during epidemic periods.

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Acknowledgments

The authors thank Morris Brown and Robert Morris of the Colorado Division of Parks and Outdoor Recreation for making the area available for study. We thank the Colorado State Forest Service for 77 worker-days of field work contributed to the study.

McCambridge, William F., Frank G. Hawksworth, Carleton B. Edminster, and John G. Laut. 1982. Ponderosa pine mortality resulting from a mountain pine beetle outbreak. USDA Forest Service Research Paper RM-235, 7 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

From 1965 to 1978, mountain pine beetles killed 25% of the pines taller than 4.5 feet in a study area in north-central Colorado. Average basal area was reduced from 92 to 58 square feet per acre. Mortality increased with tree diameter up to about 9 inches d.b.h. Larger trees appeared to be killed at random. Mortality was directly related to number of trees per acre and presence of dwarf mistletoe, but not to site index, elevation, and percent Douglas-fir in the stand.

Keywords: *Dendroctonus ponderosae, Pinus ponderosa* mortality, tree and stand characteristics.

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
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Rocky Mountain Forest and Range Experiment Station

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United States
Department of
Agriculture

Forest Service

**Rocky Mountain
Forest and Range
Experiment Station**

Fort Collins,
Colorado 80526

Research Paper
RM-236

Green Ash Seed Sources for North Dakota

James L. Van Deusen and Richard A. Cunningham

CLEMSON UNIVERSITY
DEC 28 1982
PUBLIC DOCUMENTS

USDA Forest Service
Research Paper RM-236

September 1982

Green Ash Seed Sources for North Dakota

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Van Deusen, James L., and Richard A. Cunningham. 1982. Green ash seed sources for North Dakota. USDA Forest Service Research Paper RM-236, 5 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Based on survival and height after eight field seasons, seed from the following provenances is recommended for use in growing planting stock for use in North Dakota: Aten, Nebr., Gettysburg, S. Dak.; Faith, S. Dak.; Lisco, Nebr.; Beaver Crossing, Nebr.; Belfield, N. Dak.; Prairie City, S. Dak.; Bismarck, N. Dak.; and Redfield, S. Dak.

Keywords: *Fraxinus pennsylvanica*, provenance test, Great Plains.

[1]*Headquarters is in Fort Collins, in cooperation with Colorado State University. Research reported here was conducted at the Station's Research Work Unit at Bottineau, N. Dak., in cooperation with North Dakota State University, Bottineau Branch.*

[2]*Mandan, N. Dak.*

Green Ash Seed Sources for North Dakota

James L. Van Deusen and Richard A. Cunningham

Management Implications

Of the provenances tested, NE 14 and SD 10 are probably the best choices from which to collect seeds for green ash planting stock for North Dakota. Ying and Bagley (1976) also recommend provenance NE 14 because it produced progeny that grow faster than average in six out of seven plantations. Seven other provenances are also recommended because of their good growth; SD 7, NE 15, NE 16, ND 1, SD 8, ND 6, and SD 11. The nine recommended provenances comprise the fast and medium growth clusters identified by ISODATA analysis, based on height and diameter growth. These nine provenances also overcome a possible local limitation on seed availability in that green ash seed should be available somewhere in the recommended provenances every year.

Collections from SD 10 should be made from the original shelterbelt, and probably the tree, which supplied seeds for this study. Seeds from other recommended provenances should come from native trees. Copies of the original seed collection record forms are on file at the USDA Forest Service Shelterbelt Laboratory in Bottineau, N. Dak. Based on current knowledge of seed zones, we recommend zones 1060, 1022, 532, 533, 542, 553, 584, 630, and 651 (Cunningham 1975). Seed collections from provenances ND 4, ND 2, SD 9, ND 3, and SD 12 probably should be avoided because of relatively slow growth.

Introduction

Green ash (*Fraxinus pennsylvanica* Marsh.) is a moderately fast growing, deciduous, hardwood tree that is being planted in large numbers in North Dakota for field shelterbelts, farmstead windbreaks, wildlife plantings, urban parks, and recreation areas. Survival of green ash has been outstanding on practically all sites throughout the Great Plains. Read (1958) reported that a survey of Great Plains shelterbelts in 1954 revealed overall survival of green ash averaged 77% at age 16. In North Dakota plantings, green ash survived best (88%) on deep, permeable, well-drained loams along river lowlands and stream valleys—sites similar to those on which it grows naturally. Read (1958) suggested that green ash is probably one of the best medium to slow growing windbreak species from the standpoint of survival and adaptability.

Green ash is the most widely distributed of all the American ashes (Wright 1965). Its range extends from Cape Breton Island and Nova Scotia to southeastern Alberta and Montana, and southward to central Texas and northern Florida (fig. 1). At least three different green ash ecotypes have been identified in the Great Plains (Mueli and Shirley 1937): The population from the arid northwestern part of the Great Plains is more drought resistant than that from the north-central Great Plains, which is more drought resistant than that from the south-central Great Plains. This is in line with annual rainfall in the Great Plains, which tends to increase in amount from north to south. Mueli and Shirley also found that parent trees and their progeny decreased markedly in size from south to north; the same size decrease is evident from east to west. Other provenance studies have shown pronounced ecotypic differences in susceptibility to low winter temperatures (Wright 1944). When grown in central Massachusetts, trees from the southern part of the range grew vigorously during the summer but winter-killed back nearly to the ground. The northern trees were slower growing but hardy.

Figure 1.—Distribution of native green ash (distribution map from Little, 1971).

A provenance study of green ash (Bagley 1970) utilizing seed collections from nine locations in the Great Plains showed that excellent growth could be obtained by planting seed from a green ash provenance as much as three degrees latitude north of its native site. When grown south of their native origins trees from northern provenances grew more slowly than did trees from local sources. Trees from Nebraska sources generally grew faster in North Dakota and South Dakota than trees from fifteen other Great Plains provenances (Ying and Bagley 1976).

On northern sites, the growth advantage of trees from southern provenances over trees from northern provenances may result from their ability to take advantage of the increased length of the day during the growing season. However, northern latitudes pose the threat of early freezes, extreme winter cold, or other climatic pressures to which the trees may not be adapted.

The most consistent long-term success in selecting seed sources that exhibit desirable growth, form, and survival should be achieved by using seed sources that have performed well in provenance tests conducted on sites similar to those on which most of the planting will take place.

Methods

In 1971, green ash seedlings from 19 provenances were shipped as 1+0 stock to Bottineau, N. Dak. (fig. 2 and table 1). They were supplied by Walter T. Bagley, Associate Professor, Department of Horticulture and Forestry, University of Nebraska, Lincoln, who furnished planting stock for three Nebraska plantations and to three of his out-of-state cooperators. The seeds were collected in 1968 and 1969 from as few as one and as many as ten native trees in each provenance, except the collections from SD 10 and ND 2, which were made from a single planted tree at each location. Seed trees were average or better when compared to other green ash trees near them. They had not been infested by insects or diseases, and their crowns were full and normal. Seedlots were labeled and stored separately, but the seedlings shipped to Bottineau were not identified more precisely than by provenance number.

The seedlings were too small for field planting in the spring of 1971. They were held an additional year in a transplant bed and planted by a Soil Conservation District crew May 18, 1972, on the Robert Surdahl farm 19 miles west of Bottineau.

Study area and design

The study, planned in consultation with the landowner, consisted of two single rows of trees (single row shelterbelts) oriented generally east-west. The rows are 900 feet (274 m) apart and have been separated in alternate years by grain crops and summer fallow. The soils at the test site are characterized as deep, nearly level, and moderately well drained. They are medium and moderately fine textured soils on glacial lake plains. They are high in organic matter, have high

Table 1.—Geographic locations of seed sources in the green ash provenance study at Bottineau, N. Dak.

State	Provenance	Nearest town	Latitude	Longitude	Seed zone[1]
			°North	*°West*	
North Dakota	ND 1	Belfield	46°45′	103°00′	542
	ND 2	Carson	46°30′	101°30′	542
	ND 3	Warwick	47°45′	98°45′	551
	ND 4	Fingal	46°45′	97°45′	552
	ND 5	Mandan	46°45′	101°00′	542
	ND 6	Bismarck	46°45′	100°45′	532
South Dakota	SD 7	Faith	44°45′	102°00′	630
	SD 8	Prairie City	45°30′	103°00′	584
	SD 9	Timber Lake	45°15′	101°00′	630
	SD 10	Gettysburg	44°45′	100°00′	533
	SD 11	Redfield	44°45′	98°45′	553
	SD 12	Dempster	44°30′	97°00′	1021
Nebraska	NE 14	Aten	42°30′	97°30′	1022
	NE 15	Lisco	41°00′	103°00′	651
	NE 16	Beaver Crossing	40°30′	97°15′	1060
	NE 17	Louisville	41°00′	96°15′	751
	NE 18	Hickman	40°30′	96°45′	1060
Kansas	KS 20	Haverhill	37°30′	96°45′	762
Oklahoma	OK 22	Unger	35°45′	95°45′	840

[1] *Cunningham (1975).*

Figure 2.—Locations of green ash seed collections and the North Dakota test site.

available water capacity, with moderate to slow permeability.

Elevation at the study area is about 457 m. Average annual precipitation on this site is about 16 inches (41 cm), with May through September totals averaging about 11.5 inches (29 cm).

The 19 provenances were planted in 4-tree plots randomly located within each of eight replications. Trees within rows are placed 8 feet (2.4 m) apart. Row 1 contains replications 1 through 4, while row 2 is made up of replications 5 through 8. Replication 8 contains only 12 provenances because of a shortage of trees from some provenances.

The trees have received no special cultural care since they were planted. Grain cropping and summer fallow have minimized weed and grass competition adjacent to the rows, but competition within rows has not been treated. None of the trees have been pruned, and multiple stems are common (fig. 3).

Results and Discussion

Survival

This is the most important factor to be considered when testing trees for adaptability to the severe climate of the northern Great Plains. Survival of trees from all central and northern provenances was 88% or better (table 2). All Oklahoma trees were dead by 1973, and only two Kansas trees were alive after 1975. Survival of trees from Oklahoma and Kansas was not analyzed. Most of the mortality could be attributed to the severe North Dakota winters. Excluding the Oklahoma and Kansas provenances, there was little variation in survival among the remaining 17 provenances.

Height

The 17 provenances were divided into fast, medium and slow growing groups by means of an ISODATA cluster analysis, using the combined height and diameter data for 1979. After the ISODATA analysis, additional tests were made comparing the three groups

Figure 3.—Multiple stem growth on a 10-year-old green ash.

Table 2.—Means of selected characteristics of trees from 19 Great Plains provenances of green ash after eight field seasons

Provenance	Height	Diameter at 1.5 m	Survival	Multistemed trees
	m	*cm*	*percent*	
NE 14	3.95	4.61	100	71
SD 10[a]	3.93	4.74	97	67
SD 7	3.58	4.51	100	57
NE 15	3.56	4.20	100	74
NE 16	3.55	4.34	88	79
ND 1	3.54	4.40	100	62
SD 8	3.51	4.37	100	44
ND 6	3.50	4.55	96	85
SD 11	3.45	4.25	97	53
ND 5	3.38	3.93	100	41
NE 17	3.37	3.81	100	91
NE 18	3.36	3.80	94	90
ND 4	3.26	3.49	100	48
ND 2[a]	3.23	3.64	97	48
SD 9	3.15	3.68	97	43
ND 3	3.01	3.92	100	70
SD 12	2.93	3.26	100	60
KS 20	3.60[b]	–	7[b]	–
OK 22	0	0	0	0

[a]*A single planted tree.*
[b]*Only 2 out of 30 trees were alive after 3 years. These data were not analyzed.*

in a stepwise manner using the S-method (Sheffe, 1959) of judging all contrasts. These analyses showed the three groups are statistically different ($p < 0.05$), but the differences among individual provenances at the border between the medium and slow growing groups are not distinct.

The three clusters maintained their relative positions throughout the eight field seasons (fig. 4). The fast growing group consisted of NE 14 and SD 10. The medium group was made up of SD 7, NE 15, NE 16, ND 1, SD 8, ND 6, and SD 11. The slowest group was ND 5, NE 17, NE 18, ND 4, ND 2, SD 9, ND 3, and SD 12.

After eight field seasons, trees from the fast cluster had grown on average a little more than 1.2 times taller than trees from the slow cluster. The height difference between one of the tallest provenances (NE 15) and an average provenance (NE 18) is shown in figure 5.

Diameter at Breast Height

D.b.h. and height are usually closely related in trees that are not growing in dense stands. So, it is expected that tall trees will have large diameters. This study produced a reasonably close relationship between height and diameter; the provenances that tend to be taller also tend to have large d.b.h. (table 2). D.b.h. data were not analyzed in this study except in combination with height for the ISODATA cluster analysis. As long as d.b.h. is large enough to provide adequate support for the tree crown, it is not a determining factor in recommending provenances. Another factor that may have affected d.b.h. of the trees is the number of major stems produced. D.b.h. of a tree with only one central stem generally will be larger than if the tree has produced several major stems.

Multiple Stems

All provenances had at least 40% of the trees with more than one stem originating below breast height (table 2). The nine provenances that seem best suited for North Dakota were about average, with 53% to 74% having multiple stems.

Apical dominance in opposite-leaved species such as green ash can easily be destroyed by many factors during the seedling stage and during subsequent development. If the terminal bud is killed through physical or environmental effects, and if thereafter both lateral buds develop, the tree is consequently forked. The process can continue in following years.

Winter-kill of terminal buds may cause multiple-stemmed trees. Top pruning in nursery beds may cause many trees to be forked. Browsing or breaking by animals may also cause multiple-stemmed trees. The evidence suggests that pruning lower branches often may be necessary to maintain a single stem. A multiple-stem characteristic also suggests that if potential

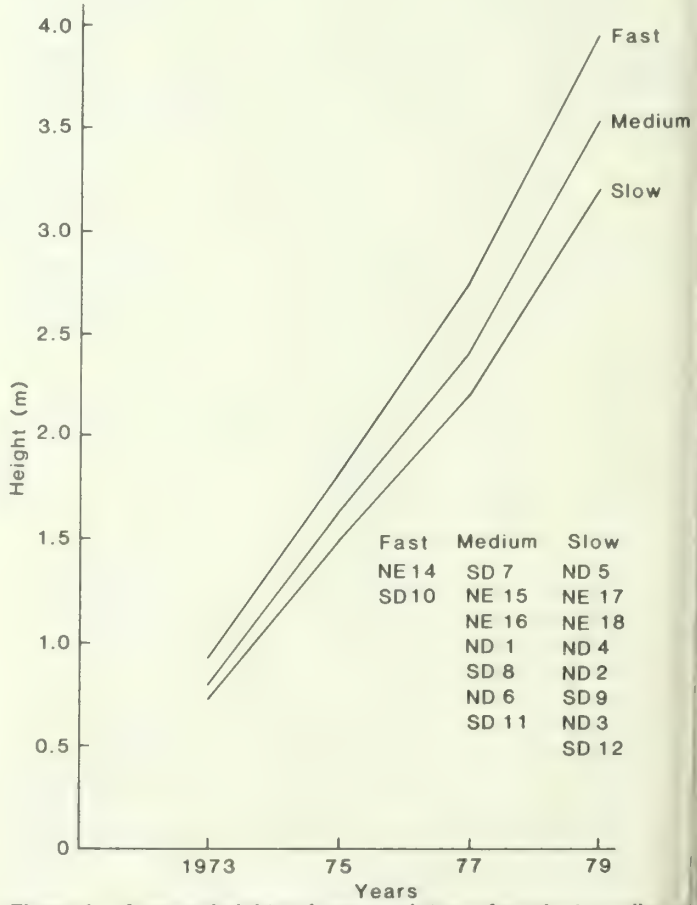

Figure 4.—Average heights of green ash trees from fast, medium, and slow growing provenances.

Figure 5.—The tree on the right (NE 15) compared with an average grower from provenance NE 18, after eight field seasons.

height and diameter growth are distributed among several stems, judicious pruning could strengthen the tendency toward height advantage shown by trees from recommended sources.

More of the trees from the Nebraska provenances had multiple stems. No observations were made on winter injury, but it is possible that terminal buds or newly emerging shoots on more trees from Nebraska provenances were killed by frost than on trees from other provenances. Deer and rodents have been seen in the area of the plantation. They could have influenced the multiple-stem characteristics, but there is no direct evidence for this.

Leaf Drop

Trees from North Dakota tended to drop their leaves earlier than did trees from Nebraska. Trees from South Dakota provenances tended to be midway between these two extremes (table 3). Ying, Schultz, and Bagley (1974) also found that leaves on trees of northern origin dropped earlier than those on trees of southern origin. Limited observations of leaf drop were made in a second year. These data are not included in this report, but they tend to reinforce the first year's trials.

Table 3.—Percent of green ash trees on which more than 50% of the leaves had dropped, by selected fall season dates, 1975

State	Trees	Date of observation				
		9/22	10/1	10/6	10/20	11/14
	number	*percent*				
North Dakota	181	22.6	65.2	97.8	100.0	--
South Dakota	168	13.7	52.4	94.6	100.0	--
Nebraska	149	0.0	17.4	74.5	99.3	100.0

Leaf drop data are necessarily subjective, but it was possible to detect a loss of approximately half the leaves from the crown. Leaf retention could be important, especially in widely spaced trees, where crown density must be maintained into the fall to prolong the soil and snow management benefits of the shelterbelt. Tree breakage caused by early fall snows that are heavy with moisture is seldom a problem in North Dakota. No data on bud break or leaf emergence were taken in the study.

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**Research Paper
RM-237**

Bald Eagle Winter Habitat on Southwestern National Forests

Teryl G. Grubb and Charles E. Kennedy

CLEMSON UNIVERSITY
DEC 28 1982
PUBLIC DOCUMENTS

Abstract

An extensive, winter survey and habitat study in 1978 located about 100 bald eagles in Arizona and 350 in New Mexico. Perching habits varied greatly but predictably. Limited in number and consistently used, roosts appear to be the most critical for management. Fluctuations in prey populations provided the opportunistic eagle with a food base changing in composition but consistent in overall availability. Study results offer some qualitative insights for habitat managers.

USDA Forest Service
Research Paper RM-237

September 1982

Bald Eagle Winter Habitat on Southwestern National Forests

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Bald Eagle Winter Habitat on Southwestern National Forests

Teryl G. Grubb and Charles E. Kennedy

Management Implications

The winter bald eagle[3] population in Arizona and New Mexico is widely scattered with few concentration areas. This population varies over time and area in response to changes in weather and prey base. Most eagles winter on northern or higher elevation Forests, where water is abundant and prey species concentrate; the Gila National Forest and the Coconino National Forest have higher wintering eagle populations than any other National Forests in the region. Identified patterns of daily and seasonal behavior will be useful for monitoring wintering eagles in the future and in assessing the value of specific use areas.

Perching is opportunistic, yet the eagles' preference for sites from which there is high visibility would allow managers to improve the characteristics of perches in areas which are marginally suitable habitat for eagles, or to shift use by providing better perches. Foraging varies less and is more appropriate for management. Wintering eagles will not remain in an area that lacks a suitable prey base. American coots and other waterfowl were the major prey used in 1978, followed by large ungulate carrion and small mammalian prey, which were more evident in the diet than were fish. Management practices beneficial to waterfowl should benefit wintering eagles in the vicinity. It may also be possible to supplement or modify the foraging activity of eagles by placing carcasses at selected locations. Research is needed on the extent of utilization of mammalian prey and on the upland wintering habits associated with this utilization.

Because of their limited number and consistent use, roosts are the most critical winter habitat component needing management protection to favor eagles. Roosts may nocturnally concentrate eagles that range over a wide area; they also provide physical protection and an opportunity for social interaction (Hansen et al. 1981). Although easily stereotyped as stands of large living trees protected from severe weather, roosts are not easy to find, because they are normally up to several miles from the area of daytime activity (Grubb (in preparation),[4] Swisher 1964). Continued monitoring of winter eagle populations on the Forests is necessary in order to locate additional roost sites.

Because of the very mobile nature of wintering bald eagles in the Southwest, their winter habitats can be affected by many management practices. Although human use of forests is generally reduced in the winter, hunting, fishing, snowmobiling, and other winter recreational activities can have negative impacts (Skagin 1981, Stalmaster and Newman 1978). Management guidelines should be based on an evaluation of the type and extent of eagle activity affected, recreational pressure, and the available alternatives.

[3] *Scientific names of plants and animals are listed in appendix.*

[4] *Grubb, T. G. Bald eagle winter activity at Navajo Lake, New Mexico. Manuscript in preparation, Rocky Mountain Forest and Range Experiment Station, Research Work Unit, Tempe, Ariz.*

Introduction

This study was undertaken to identify areas of critical habitat for bald eagles wintering on National Forest lands in the Southwest. Priority was given the wintering migrants because, in 1977, they represented a portion of the North American eagle population proposed as endangered but not addressed by a recovery team or a recovery plan. Subsequently, all bald eagles in the lower 48 conterminous states have been classified under the Endangered Species Act as threatened or endangered. Aerial surveys during the winter of 1978 resulted in population estimates of 350 wintering bald eagles in New Mexico and about 100 in Arizona, but little was known about the distribution of this population of eagles and the kinds of habitat necessary for its continued support. This study was designed to provide that information.

Grubb and Kennedy (1982) compiled the data collected by National Forest under the following headings: numbers and distribution, historical records, perching, foraging, roosting, and disturbance. That paper documents winter use areas on southwestern National Forests and gives detailed descriptions of the specific perching, foraging, and roosting sites identified. Although this paper summarizes those results, it is intended primarily to provide a qualitative discussion and interpretation with implications for management and further research.

Study Area

The 11 National Forests of the Southwestern Region of the Forest Service covered during this study are illustrated in figure 1. The ground survey effort was concentrated almost exclusively on these Forest lands; however, aerial coverage was extended to all major drainages and any reported or suspected wintering areas in both states. Vegetation of areas used by eagles typically ranges through the pinyon-juniper and ponderosa pine types, occasionally extending into Douglas-fir or sagebrush grassland types. Along major drainages, riparian areas characterized by cottonwood, willow, and sycamore associations cut through these elevational types and are frequently important to

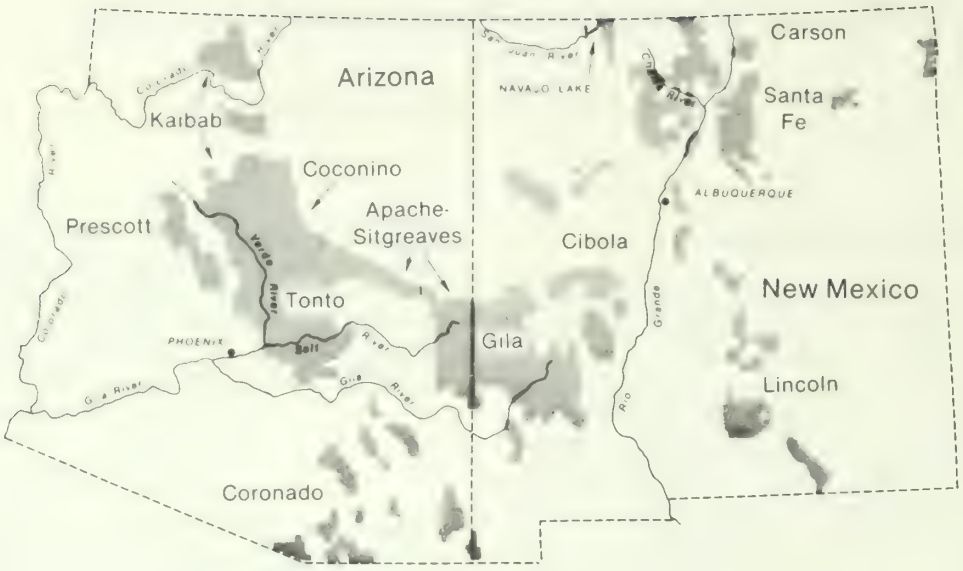

Figure 1.—Map showing location of Arizona and New Mexico National Forests.

wintering bald eagles. All but the drier Coronado and Lincoln National Forests have such drainages. Major reservoirs are common on or near the Tonto, Carson, and Santa Fe National Forests, while numerous small lakes and stock ponds are found on the Apache-Sitgreaves, Coconino, Kaibab, and Gila National Forests. Winter weather conditions vary locally with elevation and regionally with latitude, but snow and cold weather are rare on the Coronado and much of the Tonto National Forest.

Methods

This study was conducted from January 15 through April 7, 1978. The 11 field technicians working on the project were usually deployed in pairs to provide more complete coverage and because of the hazard of back country winter travel. Occasionally, personnel shifted from Forest to Forest to provide additional coverage on those Forests with large numbers of eagles. On each National Forest, the Forest biologist prioritized the known and suspected wintering areas to be checked and also suggested which Forest personnel, local residents, etc., to contact for historical information. Crews observed concentrations of bald eagles at length to determine perching, foraging, and roosting sites. They systematically surveyed areas with few or scattered wintering eagles, usually on foot or by vehicle. Some inaccessible areas suspected to have winter eagle populations were observed from the air first to determine the extent of use prior to ground checking.

Using binoculars and spotting scopes in the field, each team kept a daily log of their activities and of any observations made on eagles or their habitat. Observers summarized daily eagle sightings and recorded habitat characteristics of identified use areas on field forms. (Grubb and Kennedy 1982) Small fixed-wing aircraft (Cessna 206, 210, Skymaster)[5] and a helicopter (Hiller SL-4)[5] were used on the aerial survey flights conducted in February, March, and April for both wintering and nesting bald eagles in Arizona and New Mexico. Information gained from this aerial work helped to assign ground teams effectively as well as to assess overall population numbers and distribution. Population estimates were derived primarily from the field technicians, who used a combination of field observations, reported information, and deductive reasoning to arrive at eagle numbers in their respective areas.

Results

Areas Surveyed

Nearly 3.5 million acres were surveyed in Arizona and New Mexico through the ground study and aerial surveys (table 1). The acreage covered by aerial surveys was figured using the flight path and/or the hours flown times the average speed, with an estimated average swath of coverage of 0.5 miles (i.e., 0.25 miles on either side of aircraft). This width was based on personal experience (Grubb 1978, Grubb et al. 1975) and modified from Grier et al. (1981) to accommodate the open terrain surveyed in the Southwest. To document total effort, both the winter and spring flights are included in the aerial survey figures of table 1; thus the total figure includes some acreage observed twice. Revisits are not included in the ground acreage figures in table 1 because areas of high concentration were rechecked frequently. The 263,080 total acres from the

[5]*The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.*

ground surveys represent the actual area surveyed on the ground. This figure was derived from the acreages of lakes, reservoirs, and other water bodies and an estimated 0.25-mile swath of coverage along the observer's route of travel.

Numbers and Distribution

Wintering bald eagles usually begin arriving in Arizona and New Mexico by November. The population seems to peak in January or February, and nearly all wintering migrants are gone by the first of April (Todd 1978). The combined aerial and ground surveys of 1978 indicated a similar pattern, with a wintering population of approximately 100 bald eagles in Arizona and 350 in New Mexico. These approximations were made from actual counts of 185 adult and 167 immature eagles for the entire season in the New Mexico aerial surveys (Schmitt 1978) and from midwinter flights in Arizona showing 42 adult and 38 immature eagles.[6] The lake area near Flagstaff on the Coconino National Forest was the only area of significant winter eagle concentration in Arizona; and, even there, the birds were in small groups (5-15) scattered among different lakes. A similar concentration of scattered, small groups was evident on the Gila National Forest in southwestern New Mexico. Navajo Lake, just west of the Carson National Forest, was the only location on or near National Forest land in either state that consistently had a relatively large number of eagles (30-40 estimated) in one specific area. It appears that the most typical wintering situation in the Southwest is a large area, such as a major river course or collection of lakes, within which bald eagles are widely scattered, often perching, roosting, and feeding alone or in small groups.

An estimated distribution of the bald eagle winter population across the National Forests in Arizona and New Mexico is given in table 2. Although approximations, these figures show the relative density of wintering bald eagles on the various National Forests. Similarly, the numbers of person hours and of actual sightings indicate where eagles were expected and where they were located, respectively. In most cases, field person hour per sighting figures (FPH) also reflect the relative concentration of eagles and their accessibility for observation. In 1978 the Gila and Coconino National Forests had the largest numbers of wintering bald eagles in the Southwest. However, there were at least some wintering eagles on all the National Forests, making it difficult to rank the Forests where smaller numbers of eagles were more widely scattered and where concentrations were more variable in response to changes of weather and prey. In Arizona, the Apache-Sitgreaves National Forest also had an appreciable number of wintering eagles, followed by the Kaibab National Forest. In 1978, the Coronado, Prescott, and Tonto National Forests showed little eagle use. Similarly, in New Mexico, the Cibola, Lincoln, and the Carson National Forests (if Navajo Lake, which lies off the Carson National Forest, is not included) had few eagles in the winter of 1978; while the Santa Fe National Forest was intermediate between these Forests and the Gila National Forest.

[6] *Grubb T. G., and D. M. Rubink, unpublished data, on file at Rocky Mountain Forest and Range Experiment Station, Tempe, Ariz.*

General Habitat

As is typical throughout most of their range, bald eagles wintering on southwestern National Forests in 1978 tended to congregate around bodies of water. Although there was some variation, small- to medium-sized lakes and major river drainages were the most common hydrological situations (table 3). Elevation, latitude, and severity of the winter greatly influenced eagle distribution because smaller, nonflowing systems tended to freeze over as the winter progressed forcing the eagles to move to other areas. Unfortunately, a drought during the summer of 1977 left dry many of the lakes and stock tanks normally used on the Kaibab during the winter months. With only two notable exceptions (on the Apache-Sitgreaves and the Gila National Forests) few eagles were found on smaller drainages such as creeks, streams, side canyons, etc.; however, it was not uncommon to document several eagles frequenting an area containing several scattered ponds or tanks. In river situations, steep, narrow canyons with vertical walls separated by less than 300 feet supported few, if any, wintering bald eagles. Canyons on the Salt and Gila rivers in Arizona and New Mexico, respectively, are good examples. Qualitative analysis of notes taken in the field indicate that the number of eagles observed wintering along rivers or other bodies of water is inversely proportional to the degree of turbidity. Although this phenomenon is probably a function of prey availability, it has not been determined

Table 1.—National Forest acreage surveyed in the 1978 bald eagle winter habitat study and concurrent aerial surveys in Arizona and New Mexico

Location	Area surveyed		
	Air	Ground	Total
National Forests			
Apache-Sitgreaves	224,000	24,960	248,960
Coconino	89,600	45,440	135,040
Coronado	64,000	5,120	69,120
Kaibab	76,800	12,800	89,600
Prescott	57,600	5,120	62,720
Tonto	275,200	0	275,200
Carson	154,400	9,000	163,400
Cibola	51,200	3,200	54,400
Gila	96,000	32,000	128,000
Lincoln	0	22,400	22,400
Santa Fe	122,400	16,640	139,040
Total National Forest	1,211,200	176,680	1,387,880
Acreage surveyed off National Forests	1,987,195	86,400	2,073,595
Grand Totals	3,198,395	263,080	3,461,475

Table 2.—Estimated winter bald eagle populations, actual sightings, and field person hours (FPH) spent on National Forests in Arizona and New Mexico in 1978

Location	1978 Population estimates	Eagle sightings	FPH	FPH per sighting (Sighting per FPH)	
National Forests					
Coconino	75-125	327	540	1.65	(0.61)
Apache-Sitgreaves	25- 50	66	505	7.65	(.13)
Kaibab	10- 20	18	78	4.33	(.23)
Prescott	5- 15	8	16	2.00	(.50)
Coronado	5- 15	5	153	33.33	(.03)
Tonto	5- 15	7	0	-	-
Arizona subtotals	125-240	430	1292	3.00	(.33)
Gila	100-150	92	751	8.16	(.12)
Santa Fe	15- 25	55	393	7.15	(.14)
Carson (including Navajo Lake)	30- 50	146	444	3.04	(.33)
Cibola	5- 15	2	22	11.00	(.09)
Lincoln	5- 15	3	136	45.33	(.02)
New Mexico subtotals	155-255	298	1746	5.86	(.17)
Totals	280-495	706	3038	4.30	(.23)

Table 3.—Bald eagle winter use areas identified on southwestern National Forests in 1978[a]

Location	High use areas			Low use areas			Historical use areas		
	Lakes	Rivers	Misc.	Lakes	Rivers	Misc.	Lakes	Rivers	Misc.
National Forests									
Apache-Sitgreaves	3	1	1	1	2	3	16	1	2
Coconino	10						1		4
Coronado	1						1		1
Kaibab	1						10		4
Prescott					1			1	
Tonto				1	1		1	1	6
Carson	1	3		1				1	
Cibola									1
Gila	1	3	1	4	7	2	2	3	2
Lincoln							2	1	14
Santa Fe		1	1						2
Totals	17	8	3	7	11	5	33	8	36

Totals by use category	High: 28	Low: 23	Historical: 77
Totals by habitat	Lakes: 24	Rivers: 19	Misc.: 8

[a]*High use: consistent use by 1-2 eagles or where concentrations greater than 2 eagles occurred. Low use: occasional use, consistent but scattered use in large area, or no concentrations greater than 2 eagles. Historical (or reported use): reported areas of past use which were not checked, or if checked had no eagles. The miscellaneous category includes stock tanks, creeks, small canyons, etc.*

whether the effect is direct (e.g., resulting from fish being hidden from view) or indirect (e.g., resulting from high water driving prey from area). In Florida, Grubb (1977) found osprey hunting activity decreased when wind or clouds reduced visibility at the water surface.

Throughout the region, few bald eagles wintered along the lower river basins which run through drier, more open habitat; rather, most wintering eagles in both Arizona and New Mexico were documented at higher elevations, where the winter climate is more severe. At those higher elevations typical of the southwestern wintering situation, an appreciable number of bald eagles were observed over upland habitat well away from any significant bodies of water. Sightings of eagles perched, flying, or more typically, feeding on carrion in open rangeland were common and in some areas relatively consistent. Upland use was also noted peripheral to several rivers or reservoirs which had concentration areas, but the existence and extent of interchange could not be determined. Terrestrial wandering eagles (i.e., those not associated with any significant bodies of water) were usually seen in open habitat, including agricultural, rangeland, and pinyon-juniper areas. Many of the water-associated wintering areas were also within the pinyon-juniper type, but the ponderosa pine type was more typical. Eagles were also observed in the spruce-fir zone in higher elevations and in riparian stands, characterized primarily by cottonwood in river bottoms and along lake shores.

Perches

Nearly all the perches identified during the course of this study were in water-associated wintering areas. Daytime perch trees were usually along the shoreline, but were as far as several hundred yards from water, depending on variations in topography. Occasionally, eagles used snags in the water of artificial lakes (fig. 2). Ponderosa pine was the most typical perch tree species; it was also the most abundant and available species through most of the survey area. As shown in table 4, eagles preferred snags over living trees. In fact, if the dead-topped trees and leafless, dormant cottonwoods are included in the dead category in table 4, the percentage of perch trees which were dead increases to 77%. Depending on the activity (loafing, sunning, hunting, etc.) perches were oriented to provide all of the following, although not necessarily all at the same time: (1) a good view of the adjacent water and the surrounding area; (2) maximum exposure to the sun, especially during morning hours on cold days; (3) maximum benefit of topography and diurnal wind currents for flight. Usually eagles chose the largest trees with suitable branches. For example, on a Coconino National Forest lake with 15 dead juniper perch trees and 1 large ponderosa snag, the latter was used more frequently by more eagles (up to 6 at one time) than any of the other smaller trees. Perching eagles in the Southwest tended to be in the upper third of the perch trees and often used the highest branches. However, not all perches were in trees, i.e., it was not uncommon to see eagles on rocks along a ridge or on the ice of a frozen lake. Thus relative height of perches varied with the type of perch or its substrate, surrounding vegetation, and topography.

Roosts

Roosts were not as easily identified or located as perch sites. Only three to five specific roosts were found, but a variety of related observations provide additional insight. All the identified roosts were in ponderosa pine stands (continuous stands or isolated stringers) several hundred yards to several miles from the water resource associated with daytime activities. Occasionally, bald eagles were observed remaining in diurnal perches overnight. This happened where the

Table 4.—Species and condition of 153 bald eagle perch trees recorded on southwestern National Forests in the winter of 1978

Species	Living	Dead	Live, dead top	Species total
Ponderosa pine	27	83	8	118 (77%)
Juniper	5	17		22 (15%)
Cottonwood	6[a]	2		8 (5%)
Douglas-fir	1	1		2 (1%)
Scrub oak	1	1		2 (1%)
Pinyon pine	1			1 (1%)
Class totals	41 (27%)	104 (68%)	8 (5%)	153 (100%)

[a]*Winter cottonwoods were leafless and thus assumed the character of dead trees.*

Figure 2.—Bald eagle snag perches on an artificial lake in northern Arizona.

perch trees near small lakes were the only large or protected trees for some distance, and it also occurred at least once in apparent response to an unusually cold, calm night. More typically, eagles were observed in late afternoon flying identifiable routes up side canyons or toward forested hills, sometimes traveling 4-5 miles before being lost from view. On several occasions, birds from widely separated daytime locations flew in directions at sunset that would indicate a common roost. The widely dispersed, mobile populations of some river and upland situations suggested night roosting as individuals or in small groups as Southern (1964) has described along the Mississippi River; rather than in more typical, large, communal roost concentrations (McClelland 1973, Steenhof 1976). Those roosts identified were in protected sites, such as small canyons or draws. Usually several trees within 100 to 200 yards of each other showed evidence of use. Most roost trees were living and well foliated but with large "windows" in the canopy (figs. 3A-C).

Food Habits

During the winter of 1978, American coots were the food resource most frequently utilized by bald eagles on southwestern National Forests (table 5). A variety of other waterfowl, fish, and mammals were also taken, emphasizing the opportunistic nature of the bald eagle. On several occasions, wintering eagles adapted to a new source of prey, such as a deer carcass along the shore of a waterfowl lake; they reacted to a reduction in waterfowl by supplementing the diet with lagamorphs. Some lakes traditionally used by both waterfowl and eagles were dry much of the winter; yet when those lakes filled rather quickly from heavy rains and the waterfowl returned, bald eagles soon appeared. A more typical situation of which the eagles took full advantage was the concentration of waterfowl in small areas of open water as lakes and stock tanks froze over (fig. 4).

Figure 3A.—Ponderosa pine roost trees in a typical bald eagle roost in northern New Mexico.

Figure 3B.—High altitude aerial view of the same roost showing its proximity to a nearby lake and foraging area.

Figure 3C.—Low altitude aerial view [of the same roost] showing the roost location in a protected draw. The snag in the foreground was one of four high use roost trees within the stand.

Table 5.—Prey species identified in castings or remains at bald eagle wintering areas and predation attempts observed on southwestern National Forests in 1978[a]

Group Species	Observed attempts		Castings		Remains		Total	
Birds	22	(58%)	247	(89%)	71	(76%)	340	(83%)
American coot	19		203		66			
Mallard					2			
Pintail			[c]					
Unidentified waterfowl	3[b]		44		3			
Fish	12[b]	(32%)			5[b]	(5%)	17	(4%)
Carp					[c]			
Bluegill					[c]			
Pumpkin seed					[c]			
Brown bullhead					1[b]			
Northern pike					3			
Rainbow trout					1			
Golden shiner	6							
Mammals	4[b]	(10%)	25	(9%)	10	(11%)	39	(9%)
Cottontail/jackrabbit			18		5			
Elk deer[d]			5		1			
Antelope[d]			1					
Wood rat					1			
Coyote[d]					1			
Cow[d]			1		1			
Horse[d]					1			
Invertebrates			7	(2%)	8	(8%)	16	(4%)
Freshwater mussel[e]			5		7			
Scarab bettle			1					
Jerusalem cricket			1					
Totals[f]	38		279		94		411	

[a]*It was rarely possible to determine the number of individual animals represented, so totals and percentages based on castings and remains must be considered approximate.*
[b]*Additional observations not recorded in field notes.*
[c]*Number of observations not recorded.*
[d]*Known only as carrion from road or winter kill.*
[e]*Grubb and Coffey 1982.*
[f]*Add group values only.*

Two methods of capturing coots were observed. In the most frequently used technique, an eagle flew low over the coots, flaring slightly, then lowering its talons to grasp a bird. This was accomplished in a relatively continuous, flowing motion where only the talons, if anything, hit the water. The other method involved an eagle circling or almost hovering over some coots and dropping onto them. This technique often resulted in a dunking for the eagle. With the probable exception of cottontails and jackrabbits, most mammalian prey was consumed as carrion. In a few areas, wintering eagles were apparently hunting lagamorphs quite consistently, as Edwards (1969) recorded in an essentially terrestrial winter population in the Great Basin of Utah.

Behavior

The bald eagles wintering in the Southwest in 1978 were both widely scattered and highly mobile. Some seasonal variations in numbers and distribution were due to transient eagles migrating to or from wintering areas. However, weather conditions, habitat suitability, and prey availability were the key factors in both migratory and local movements of wintering eagles within the region. Seasonal migration from the winter-

Figure 4.—A partially frozen lake in northern Arizona where wintering bald eagles frequently took advantage of the concentrated waterfowl.

ing grounds was associated with the warmer weather of early spring, while changes in temperature during the winter months affected diurnal activity. On extremely cold days, wintering eagles were relatively immobile, foraging very little, and remaining on perches or on the ice of a frozen lake through most of the day. On unusually warm days, general daytime activity increased, and the birds were frequently observed ranging away from the usual perching and foraging areas. In a few instances, heavy and prolonged snow seemed to cause movement away from lakes and rivers. A generalized diurnal activity pattern described primarily from observations in several areas of consistent concentrations is shown in table 6. Scattered individuals or small groups followed much the same pattern, but their distribution, small numbers, and apparent nomadic existence suggested opportunistic, noncommunal roosts.

Bald eagles wintering around lakes and reservoirs showed an habitual pattern of activity in contrast to a more mobile, opportunistic pattern of activity in eagles wintering along rivers. Eagles associated with standing bodies of water were more predictable, favoring specific perches, patterns of foraging, flight routes, etc. When disturbed, these eagles showed a tendency to return to their original location after the disturbance passed. Eagles wintering near rivers were apparently not so habituated to a specific set of habitat conditions. Individual birds were observed perching in a variety of locations with no noticeable preference for perviously used perches. On several occasions, eagles flushed by field personnel showed no inclination to remain in the area; instead these birds flew off along the river and did not return after the disturbance. Although on a regional scale it was not possible to quantify sightings into actual numbers of birds, there was a definite trend for immature eagles to occur in greater numbers around lakes and reservoirs than along river drainages.

Table 6.—Observed dirunal activity pattern of wintering bald eagles on southwestern National Forests in 1978

Time of day	Activity
Predawn	Leave roost for perching and/or foraging areas.
Sunrise	On loafing or hunting perches around foraging area or dispersing for foraging area.
Early-midmorning	Foraging.
Midmorning-midafternoon	Little activity, sunning, preening, occasional soaring.
Late afternoon	Increased activity, more foraging.
Sunset	Often begin movements toward roosting area.
Twilight into darkness	Usually on roost for night.

Discussion

Numbers and Distribution

The population estimates shown in table 2 are presented to document the findings of this pioneer effort in the Southwest and to provide a benchmark for comparison and refinement with future surveys. A comparison of the states' subtotals with the aerial survey results (80 in Arizona and 352 in New Mexico) suggest that in Arizona either the aerial results underestimated the population or the estimate derived from ground studies was exaggerated. Both explanations probably apply, but it does appear the majority of wintering bald eagles in Arizona are on National Forest lands. In New Mexico, the aerial surveys of 1978 and subsequent efforts (Hubbard 1979, Pramstaller et al. 1979) indicate a significant portion of the wintering eagle population is found off National Forest lands.

Regardless of actual numbers eventually documented, table 2, which is based on 1978 field data and supported by historical information, does provide a representative assessment of the relative importance of the various National Forests to wintering bald eagles. It should be noted, however, that specific field labor hour figures by themselves can be misleading because of several inherent biases: variation in observers and observation techniques, the inclusion of probable repeat sightings of the same eagles on different days, and the intentional concentration on areas known or expected to have wintering eagles. In addition, a small number of field labor hours can also exaggerate resulting indices when a few birds are seen (e.g., Prescott National Forest where the 2.00 FPH/sighting indicates a greater fequency of eagle encounters than actually occurs across the entire Forest). In contrast, numbers may be conservative for some National Forests. For example, many high country lakes were frozen and snow covered by the onset of this study on the Apache-Sitgreaves National Forest; and many other, normally used lakes were very low or dry from summer drought conditions on the Kaibab. This may have caused eagles which normally winter on this Forest to move elsewhere.

General Habitat

Few eagles appear to winter at lower elevations within the two states, despite the rather unique dichotomy of wintering habitats available. One might expect bald eagles migrating to Arizona for the winter to frequent the warm, dry, central desert lakes, rivers, and riparian areas; but the vast majority of wintering eagles remain in the ponderosa pine forests where they must endure snow and cold temperatures. The key to this behavior apparently lies in the prey base, which both fluctuates with (see Food Habits discussion), and is concentrated by normal winter conditions. Locally, the severity of winter conditions is directly related to elevation; whereas, regionally or geographically, latitude is the independent variable. The winter concen-

tration of many wildlife species, particularly waterfowl and big game, is well established (Leopold 1933, Linduske 1964, Moen 1973, and Taylor 1965). Thus, potential avian and mammalian prey species are most abundant and available within a range of winter conditions from those insufficient to cause concentration to those causing emigration or death. Figure 5 illustrates this relationship. Eagle numbers and concentrations in the Southwest appear to increase slowly to a peak prior to the time at which winter conditions cause prey emigration. This conceptual relationship presumes existence of sufficient water resources, roost sites, perches, freedom from disturbance, etc., and does not include a consideration of natural fish resources, which are much less affected by winter conditions than are avian or mammalian prey. Nevertheless, this hypothesis derived from field observations explains the distribution of wintering bald eagles in the Southwest.

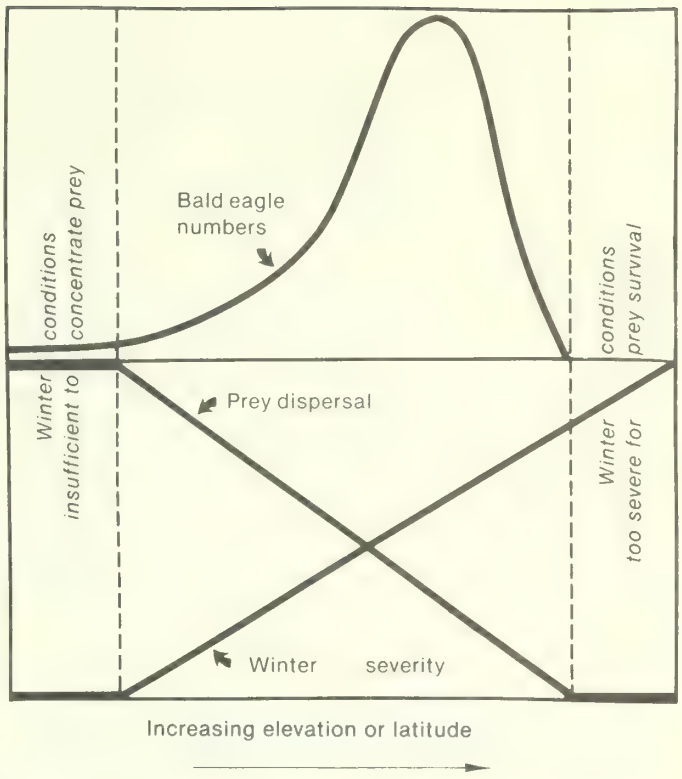

Figure 5.—A postulated relationship between elevation (local) or latitude (regional), prey dispersal (waterfowl and big game), and winter bald eagle distribution in the Southwest.

Perches

Perches are probably the least critical component of bald eagle winter habitat; and, although perching is the most typically observed activity, lack of perch sites rarely limits eagle populations. In a nesting situation, eagles appear to select trees on the basis of general characteristics such as relative height, stout branching, proximity to water, and stand heterogenity (Grubb 1980); there is no species preference per se. Similarly, winter perches which are used for a variety of loafing and foraging activities are chosen on the basis of availability, with visibility appearing to be the common denominator of several observed trends in perch characteristics. Normally, bald eagles perch in large trees and apparently prefer snags or dormant, deciduous species. However, they also frequently perch on a variety of other substrates such as lake ice, ridge top boulders, open-range junipers (fig. 6), etc.

Certainly water resources, proximity of foraging and roosting areas, weather conditions, and human activity have contributory effects on the selection of winter perches (Servheen 1975, Stalmaster and Newman 1979), but a pattern emerges from the observed range of perches which suggests the height of the perch is inversely proportional to the visibility from it (fig. 7). This is not to deny that visibility increases with height; however, over a range of environmental situations, minimum or obligate perch height does show a reciprocal relationship with visibility from the perch. This visibility is influenced by at least three interrelated habitat characteristics: openness, height of substrate, and height of surrounding vegetation. As the first two increase, the need for tall perches is reduced because visibility is maintained by the openness of the habitat or the height of the hill (e.g., perching on lake ice or on the rock of a high outcrop). However, an increase in the height of surrounding vegetation requires higher perches to sustain a view beyond the adjacent foliage. Recognition of these perching characteristics should facilitate an assessment of potential habitat and may provide a management tool for improving perch sites in marginal areas.

Figure 6.—Adult bald eagle on a typical low juniper perch in open range land in northern New Mexico.

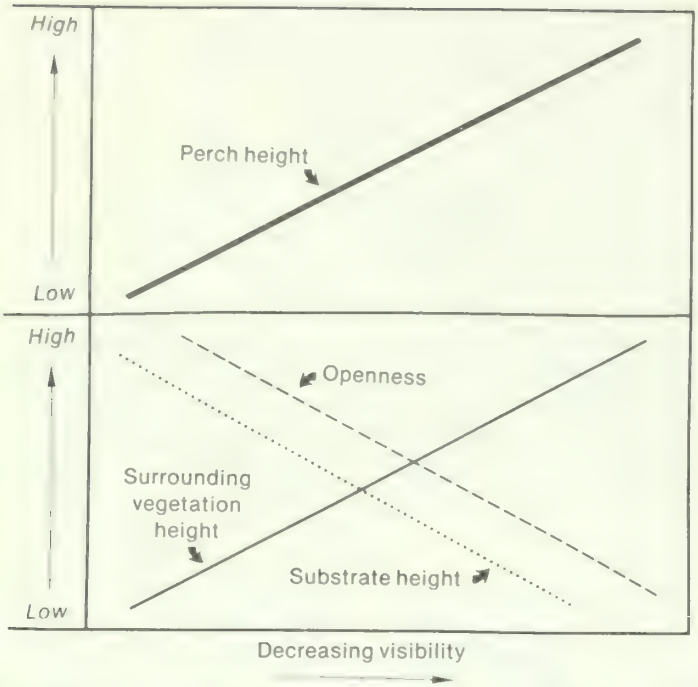

Figure 7.—The apparent relationship when perch height is considered dependent on visibility, which is influenced by openess, substrate height, and surrounding vegetation height.

Roosts

In contrast to perches, roosts are usually in live trees, in relatively dense stands, in protected situations such as draws or small drainages, often several miles from the daytime loafing and foraging areas. Communal roosts often represent consistent, high-density use by eagles and are one of the most important attributes of winter eagle ecology for management and/or protection (Steenhof 1978). Foraging and perching habits within an area may vary significantly through the winter, but those eagles involved may continue to use the same communal roost throughout the season (Edwards 1969). Unfortunately in the small, scattered population situation of the Southwest, roosts are very difficult to locate. A significant investment of time is required to find the eagles and become familiar enough with their diurnal pattern of activity to eventually follow them to roost. The difficulties are compounded by roosting flights' often being after dark or before dawn. Thus remains the irony that the most stable and perhaps the most critical component of eagle winter habitat is the least known in the Southwest. Roosts located distant from areas of observed concentrations may be subject to incompatible land practices because eagles are not obviously associated with the area. Roosts may also be the key to documenting the widely dispersed individuals and small groups ranging over terrestrial or upland habitat. Whether these birds come together in communal roosts is as yet unknown; but if they do, such roosts could be critical to the physical and behavioral maintenance of that population.

Food Habits

As mentioned in the discussion of prey dispersal and winter severity, the bald eagle's avian and mammalian prey base also fluctuates with winter weather conditions, and in so doing, provides additional advantage to the eagles wintering in the harsher climates of the Southwest. In mild to normal winters or early in the season, many lakes and rivers support large populations of waterfowl which are a major source of prey for bald eagles. As the severity of winter increases, the waterfowl become more vulnerable in concentrations on the small areas of remaining open water. If as the season progresses, or during a severe winter, most bodies of water are frozen over, the waterfowl emigrate, leaving the eagles with a reduced avian prey source. However, such conditions usually lead to an increase in both the winter kill of big game and the vulnerability of small mammals such as cottontails and jackrabbits. Thus, prey populations fluctuate as winter conditions dictate, but the opportunistic eagle has a consistent, although variable, prey base (fig. 8).

The extent to which mammalian prey or carrion was utilized during this study was difficult to ascertain because the nature of this food source leads to widely dispersed foraging activity. There may be a sizeable population of wintering eagles wandering throughout the rangelands of Arizona and New Mexico and feeding on large ungulate and livestock carcasses or taking small mammals. Associated with this variation in prey resources is a variation in mobility. Eagles which feed on waterfowl or fish tend to congregate and remain around specific water resources, whereas those utilizing mammalian prey appear to be widely ranging. The

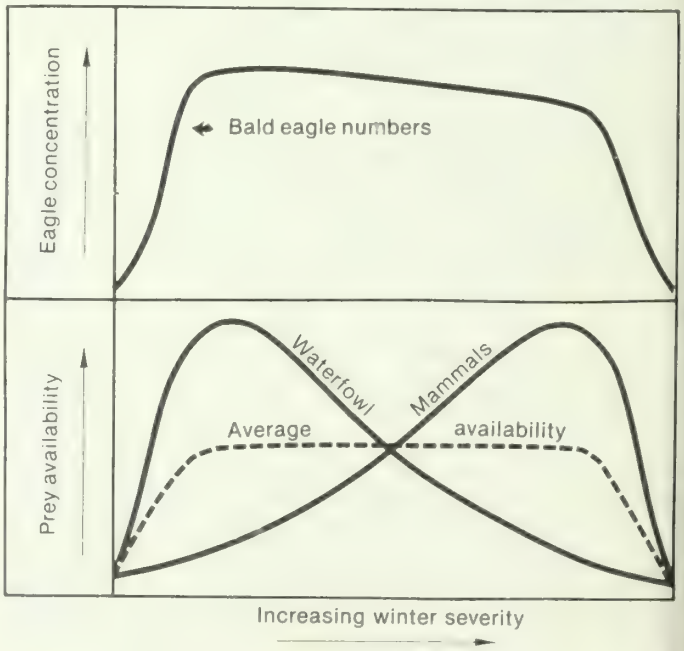

Figure 8.—The apparent fluctuation of avian and mammalian prey leading to a relatively stable, average prey base as winter severity varies and the resultant, postulated change in bald eagle concentration (or dispersal).

latter necessarily must be more opportunistic in the role of scavengers, yet communal roosting in this situation may also function as a means of exchanging information on the whereabouts of food resources (Ward and Zahavi 1973). It is also possible that eagles in the more traditional wintering areas are utilizing habitat away from water during periods of the winter season. The variety in diet and the eagle's opportunistic nature evidence evolution away from a strictly "sea eagle" bond to water (or the reverse, i.e., incomplete evolution toward fish-eating from a generalist's role[7]). Fish appear to be utilized by bald eagles wintering in the Southwest, but initial data indicate avian and mammalian prey to be more important. Unfortunately, fish provide little roughage and, therefore, are rarely evident in castings (table 5) (Lish 1975, Steenhof 1976).

Behavior

Behavior patterns observed during this study are similar to those throughout the bald eagle's wintering range (Spencer 1976); however, the lack of large concentrations and the extent of widely scattered individuals and small groups are relatively unusual. Both factors compound the difficulty of quantifying habitat needs and behavioral characteristics. The tendency of river dwelling eagles to flush and not return for at least an appreciable time probably reflects the more variable habitat and prey conditions found along river situations during winter months. In contrast, lakes and reservoirs provide more stable conditions, permitting increased habituation to the local environment and subsequent development of identifiable behavioral patterns. The higher proportion of immature eagles in these situations may be associated with the greater concentrations of both eagles and prey, and the more consistent activity patterns. The less experienced immature eagles would seem to have a better chance of finding food and roosting or perching safely. The theoretical advantage of group roosting and foraging for transmittal of prey locations (Ward and Zahavi 1973) has been supported by studies of wintering eagles in western Washington (Hansen et al. 1981, Servheen 1975). The harsher wintering conditions and the lack of social interaction along river habitats may well select against all but the more experienced adults and the most competitive immature bald eagles.

Recommendations

This study, although extensive, was limited to one field season; therefore, much of the information presented has necessarily been qualitative instead of quantitative. Only subsequent years of data can establish norms and trends in habitat utilization, population numbers and distribution. To facilitate future interpretations, more research is needed on numbers, distribution, season/diurnal movements, perching, roosting, and foraging habits. From a management standpoint, location of roosts is a high priority, followed by locating foraging areas and then perching/loafing sites. Specific habitat and population characteristics must eventually be determined for those scattered eagles consistently utilizing upland or terrestrial habitat. Both aerial and ground techniques should be employed on any future habitat studies. Aerial surveys can document the numbers, distribution, and seasonal fluctuations; whereas, ground observation is necessary to describe food habits, behavior, and specific use areas. Aerial surveys should be flown in late fall (October-November), midwinter (January-February), and early spring (March-April). Actual timing of these flights should be based on the severity of the winter and local habitat conditions, but field personnel conducting ground surveys and habitat analyses should be deployed by November 1. The aerial surveys can determine the best areas for ground observation throughout the winter season.

[7]*Sergey Postupalsky, Wildlife Ecologist, University of Wisconsin, February 21, 1981, personal communication.*

Acknowledgments

Funding for this project was provided by the Southwestern Region (Region 3) of the USDA Forest Service and administered by the Rocky Mountain Forest and Range Experiment Station (RM). Concurrent but independent aerial surveys were planned and executed under the auspices of the Southwest Bald Eagle Recovery Team. However, RM coordinated these efforts and the Forest Service shared in the expense of the flights along with the Bureau of Land Management, the U.S. Fish and Wildlife Service, the New Mexico Department of Game and Fish, and the Navajo Nation.

The authors thank RM project employees Michael Coffey, Norris Dodd (who took the photographs for figs. 2 and 4), David Garcelon, Allan Gast, Dick Hanna, Howard Hunt, Tony Pippett, Rick Prigge, Gary Rosenberg, Carol Rudolph, and John Werner for the innumerable hours volunteered to achieve dawn-to-dusk observation, for enduring the rigors of back-country, winter travel to make such data collection possible, and for their enthusiastic committment to the project. Richard Knight, Research Biologist, Washington Game Department; Donald Spencer, retired Biologist, U.S. Fish and Wildlife Service; and William Zeedyk, Director Wildlife Management, U.S. Forest Service, Region 3, provided helpful reviews of an earlier manuscript.

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Appendix

Fauna List[1]

Bald eagle	*Haliaeetus leucocephalus*
American coot	*Fulica americana*
Mallard	*Anas platyrhynchos*
Pintail	*Anas acuta*
Carp	*Cyprinus carpio*
Bluegill	*Lepomis macrochirus*
Pumpkinseed	*Lepomis gibbosus*
Brown bullhead	*Ictalurus nebulosus*
Northern pike	*Esox lucius*
Rainbow trout	*Salmo gairdneri*
Golden shiner	*Notemigonus crysoleucas*
Elk	*Cervis canadensis*
Deer	*Odocoileus* spp.
Pronghorn (Antelope)	*Antilocarpa americana*
Cottontail	*Sylvilagus* spp.
Black-tailed jackrabbit	*Lepus californicus*
Woodrat	*Neotoma* spp.
Freshwater mussel	*Anodontia corpulenta*
Scarab beetle	Family Scarabaeidae
Jerusalem cricket	Family Gryllacrididae

Flora List[2]

Ponderosa pine	*Pinus ponderosa*
Pinyon pine	*Pinus edulis*
Juniper	*Juniperus* spp., *J. utahensis*
Douglas-fir	*Pseudotsuga menziesii*
Cottonwood	*Populus* spp.
Scrub oak	*Quercus* spp.

[1]*A.O.U. (1957), Burt and Grossenheider (1964), Lee et al. (1980), and Pennak (1953).*
[2]*Preston (1965).*

Grubb, Teryl G., and Charles E. Kennedy. 1982. Bald eagle winter habitat on southwestern National Forests. USDA Forest Service Research Paper RM-237, 13 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

An extensive, winter survey and habitat study in 1978 located about 100 bald eagles in Arizona and 350 in New Mexico. Perching habits varied greatly but predictably. Limited in number and consistently used, roosts appear to be the most critical for management. Fluctuations in prey populations provided the opportunistic eagle with a food base changing in composition but consistent in overall availability. Study results offer some qualitative insights for habitat managers.

Keywords: Bald eagle, winter habitat, behavior, foraging, roosting, winter distribution, habitat management.

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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Leaf Area Determinations for Subalpine Tree Species in the Central Rocky Mountains

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Research Paper RM-238
Rocky Mountain Forest and
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Research Paper RM-238

September 1982

Leaf Area Determinations for Subalpine Tree Species in the Central Rocky Mountains

Merrill R. Kaufmann, Principal Plant Physiologist
Carleton B. Edminster, Principal Mensurationist
and
Charles A. Troendle, Principal Hydrologist
Rocky Mountain Forest and Range Experiment Station[1]

Abstract

Needle area of Engelmann spruce, subalpine fir, and lodgepole pine and leaf area of aspen are predicted from d.b.h. or tree height. Leaf area index can be calculated from stand basal area.

[1]*Headquarters is in Fort Collins, in cooperation with Colorado State University.*

Leaf Area Determinations for Subalpine Tree Species in the Central Rocky Mountains

Merrill R. Kaufmann, Carleton B. Edminster,
and
Charles A. Troendle

Management Implications

The ability to predict leaf area index from simple measurements has great potential for improving hydrologic and growth/yield models. Specific knowledge of leaf area index makes possible a far better understanding of water vapor loss, interception, CO_2 fixation, and radiation balance of forest stands. These processes are critical elements in hydrologic models and in understanding forest canopy and understory growth.

This study reports development of equations which permit calculating both total leaf area and effective projected leaf area for Engelmann spruce, subalpine fir, lodgepole pine, and aspen. Total leaf area is the area of all needle or leaf surfaces. Effective projected leaf area is the area of shadows cast by randomly oriented needles or leaves.

The leaf area equations utilize tree basal area, d.b.h., or tree height as independent variables. These data are easily measured and are routinely collected in forest management activities. Therefore, leaf area of subalpine forest trees can be readily determined.

Leaf area index is the ratio of leaf area to land area. Total and effective projected leaf area indices can be determined for the conifers using stand basal area as an independent variable. For aspen, basal area per tree is required, along with stand basal area, for predicting leaf area indices.

Introduction

Until recently, knowledge of leaf or needle area of trees was of little interest in forest research or management. Most studies of forest canopy processes were conducted at levels requiring little specific information about foliage surface. During the past few years, however, estimates of leaf area have become increasingly important. Models of physical and biological processes of trees and forests are being developed at levels requiring data that characterize canopy configuration and the amount of foliage involved in exchange processes.

Hydrologic models are based increasingly upon individual processes involved in the storage and movement of water in soil and plants. For example, some studies focus on the consumptive use of water by foliage of individual trees in the context of plant and environment interaction. Until recently, estimates of growth and yield of stands required knowledge of stand density and crown closure as indicators of site utilization (Munro 1974). Attention now is turning to yield of biomass and the efficiency of wood production in relation to amount of foliage (Waring et al. 1980).

The selection of methods for estimating leaf area depends upon the particular needs for leaf area data. For studying gas exchange or other processes on small amounts of foliage, accurate, direct measurements of leaf or needle area often are needed. In such cases, leaf area can be determined by measuring and counting individual leaves or needles, or foliage can be harvested at the end of the study for measurement with an electronic leaf area meter. For large trees, however, the measurement of individual leaves is impractical, and destructive sampling is often unacceptable. At the stand level, the only reasonable approach for estimating leaf area is the use of predictive empirical relationships.

One of the most useful and accurate methods of estimating leaf area of trees is based on a physiological relationship. Under normal conditions, the relative size of various plant parts remains balanced because the parts are physiologically interdependent (Kaufmann and Troendle 1981). Loss of water from foliage by transpiration requires that water be supplied through the sapwood conducting tissue in the trunk. Leaf area of the crown is limited by the capacity of the sapwood to supply water, because water stress limits foliage growth when the sapwood transport capacity is inadequate. Similarly, sapwood size is affected by the amount of foliage available to produce dry matter for trunk growth. A growing number of studies now demonstrate that a close relationship exists between leaf area and cross-sectional area of sapwood conducting tissue in the trunk (e.g., Gholz et al. 1979, Rogers and Hinckley 1979, Waring et al. 1977).

Recently, Kaufmann and Troendle (1981) showed that the leaf-area/sapwood-area relationship was the same for portions of the crown as it was for the entire crown in four subalpine tree species in the central Rocky Mountains. The study reported here was undertaken to determine the simplest relationships for estimating leaf area of subalpine tree species in the central Rocky Mountains using rapid and nondestructive measurement techniques. Attention was given to

selecting parameters for estimating leaf area that were readily available and related to forest management activities. During the past decade, considerable interest has developed in biological and physical processes at the individual tree level. Therefore, most of the results presented here characterize leaf area of trees as functions of individual tree variables. However, leaf area also can be related to stand characteristics such as basal area and size classification.

Methods and Materials

Trees were sampled at the Fraser Experimental Forest, 8 km southwest of Fraser, Colo., during August and September of 1979 and 1980. The sampling procedures summarized here are given in detail by Kaufmann and Troendle (1981). Data were collected on four subalpine tree species—Engelmann spruce (*Picea engelmannii* Parry), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), and aspen (*Populus tremuloides* Michx.). Trees were selected from a wide range of stands and physiographic situations and represented a broad spectrum of size, age, and growth rate. Sample size ranged from 12 to 15 trees per species, and tree size ranged from small saplings several meters tall to large, mature trees (table 1).

Trees were carefully felled, and foliage samples were collected. For small trees, all the foliage was collected, including small branches. For the largest trees, fresh foliage exceeded 5 m^3 in volume, and subsampling was required (see Kaufmann and Troendle (1981) for details of the subsampling procedure). Foliage samples were dried for 1-5 days in a small insulated building equipped with electric heaters. This facilitated removal of the branches, which were discarded. Final foliage dry weight was determined after an additional period of at least 48 hours at 70-75° C.

Trunk measurements included total height, depth of live crown (difference between total height and height to base of live crown), and outside diameters and sapwood areas at breast height (1.37 m) and at the base of the crown. Leaf areas of tree crowns were determined by measuring the dry weight of all foliage (or estimating total dry weight from subsamples) and multiplying by a total leaf area : dry weight conversion factor. These factors were as follows (Kaufmann and Troendle 1981):

Engelmann spruce	9.996 $m^2 \cdot kg^{-1}$
Subalpine fir	8.859 $m^2 \cdot kg^{-1}$
Lodgepole pine	9.518 $m^2 \cdot kg^{-1}$
Aspen	21.94 $m^2 \cdot kg^{-1}$

The ratio of total leaf area to projected leaf area was determined for each species. The procedures used here for estimating projected leaf area differ from those apparently followed in other studies. Gholz et al. (1976) and other researchers appear to have determined the ratio by measuring the total area of conifer needles and then measuring the projected area of flattened needles. For example, Gholz et al. (1976) used a ratio of about 2.3 for western hemlock, Douglas-fir, and silver fir. Thickness of needles (compared to a flat leaf) could account for this 15% increase in area above that of two parallel planes having the same outline. Conventionally, total leaf area of angiosperms is twice the projected area.

Estimates of projected area of foliage obtained by this method assume that all foliage is oriented horizontally. In studies involving canopy processes, this assumption often is unacceptable. For example, attenuation of solar radiation passing through a canopy is dependent not on the projected area as determined above, but on the effective projected area, which is also dependent upon leaf orientation. Radiation intensity in the lower portion of a canopy is a function of the actual shadows cast by foliage in the upper canopy, not by the potential area of shadows if all foliage was oriented horizontally.

The equations given below provide methods for estimating total leaf area and effective projected leaf area. Total leaf area was estimated using the leaf-area : dry-weight conversion factors given above. Effective projected leaf area was determined by assuming random orientation of foliage. Kimes et al. (1979) concluded that needle orientation of lodgepole pine and probably many other conifers was random, although Norman and Jarvis (1974) provided data for Sitka spruce suggesting a nonrandom orientation. Perhaps aspen leaf orientation is nonrandom, but no data are

Table 1.—Sample size, maximum d.b.h., basal area per tree (BA), sapwood area at 1.37 m (SA), tree height (TH), and total leaf area (TLA) of the sample trees. Minimum d.b.h. was 1-3 cm, and minimum TH was 2-3 m

	Engelmann spruce	Subalpine fir	Lodgepole pine	Aspen[a]
Sample size	15	12	14	14
Maximum d.b.h. (cm)	51.1	49.8	49.8	42.7
Maximum BA (cm^2)	2,047	1,947	1,947	1,430
Maximum SA (cm^2)	1,242	363	662	461
Maximum TH (m)	32.5	30.2	29.6	26.5
Maximum TLA (m^2)	1,196	903	410	83.4

[a] *Includes only aspen trees sampled in this study. These data were pooled with those of Johnston and Bartos (1977) for all analyses.*

available describing orientation. However, errors associated with assuming random orientation of needles and leaves are likely to be small.

Effective projected leaf area was calculated by first measuring the actual projected area of horizontal needles or leaves. For spruce, fir, and pine, this projected area was measured without laying the needles flat—twists and curves were allowed to occur. By this procedure, the ratio of total needle area to actual projected area of horizontal needles was 3.21 for Engelmann spruce and subalpine fir and 3.34 for lodgepole pine. Random distribution of needles or leaves would result in leaf angles uniformly distributed between $-90°$ and 90° from the horizontal. Accordingly, the shadow cast by direct beam radiation may be determined as the cosine of this angle. Therefore, the mean shadow length, obtained by integrating the cosine over the range of from $-90°$ to 90°, is 63.66% of leaf length. Finally, effective projected leaf area of randomly oriented foliage is calculated as 0.6366 times the actual leaf area for unflattened needles or leaves held horizontally. The ratios of total leaf area to effective projected leaf area are as follows:

Engelmann spruce	5.04
Subalpine fir	5.04
Lodgepole pine	5.25
Aspen	3.14

Standard stepwise regression techniques were used for analyses, with total leaf area as the dependent variable. Curves were forced through the origin. By this procedure, trees under 1.37 m tall are ignored when determining leaf area or leaf area index of stands. For many forest processes, this is suitable because very small trees behave as understory vegetation. Leaf area of small trees can probably be estimated using diameter measurements made near the ground. An extensive series of analyses evaluated single and multiple parameters for estimating leaf area. These parameters included diameter at breast height, basal area at breast height (a function of d.b.h.), diameter at the base of the crown, sapwood area at breast height, total tree height, and depth of live crown. After analyses were complete, equations were determined for both effective projected and total leaf areas using the appropriate ratios given above.

Results

A linear relationship between needle area and basal area per tree was observed for Engelmann spruce, subalpine fir, and lodgepole pine (figs. 1, 2, and 3). Equivalent tree diameters are indicated in the upper scale. Comparison of regression equations with tree basal area, total tree height, and depth of live crown as independent variables indicated that suitable estimates of needle area can be made simply using basal area measurements. Regression equations relating needle area to basal area are given in table 2. Because d.b.h. and basal area per tree are directly related [$BA = \pi\ (d.b.h./2)^2$], needle area can also be determined directly from d.b.h. using a separate set of equations. These equations are also given in table 2.

Aspen data collected in this study were supplemented with those of Johnston and Bartos (1977) for 18 trees sampled in northern Utah and northwestern Wyoming. With the exception of two trees, the data were described by a curvilinear relationship of total leaf area to tree basal area (fig. 4 and table 2). The two trees not included in the analyses were sampled from an unusual site on the middle of a south-facing, 35% slope and characterized by a continuous moisture seep. These trees had very deep crowns and dense foliage, probably the combined result of a continuous supply of water and high visible radiation.

The relationship between leaf or needle area and tree height also was calculated (table 3). For subalpine fir and lodgepole pine, R^2 values were about as high for equations using tree height as for those using basal area, indicating that either equation is suitable for estimating needle area. For Engelmann spruce the R^2 value declined slightly from 0.904 to 0.869, and for aspen the R^2 value decreased from 0.944 to 0.867. For the latter two species, tree basal area or diameter measurements are slightly better than tree height for estimating leaf area.

The relationship of needle or leaf area to basal area per tree may be used to calculate leaf area index as a function of stand basal area. Leaf area index is the ratio of total or effective projected leaf area to the surface area of land, and the units are dimensionless (from $m^2 \cdot m^{-2}$). For the three conifers, leaf area index is independent of individual tree size, because leaf area per tree is a linear function of tree basal area. Leaf area index as a function of stand basal area for the conifers is given in figure 5. Appropriate equations relating leaf area index to stand basal area are given in table 4 (SI units) and table 5 (U.S. standard units).

In aspen, leaf area per tree is curvilinearly related to tree basal area (fig. 4). Consequently, the relationship of leaf area index to stand basal area varies with tree diameter class (fig. 6). Large trees have less leaf area per unit basal area, and a stand of large trees has a lower leaf area index than a stand of smaller trees with a comparable stand basal area.

Discussion

These results indicate that effective projected or total leaf area for the major subalpine tree species in the central Rocky Mountains can be estimated using easily measured variables. The equations presented above permit calculating total leaf area of a tree from diameter, basal area, or height. Leaf area index can be obtained from stand basal area. In cases where vertical distribution of foliage within the canopy is required, it is likely that trunk diameters within the crown would be suitable for estimating leaf area above the point of measurement, although appropriate equations have not been developed. Kaufmann and Troendle

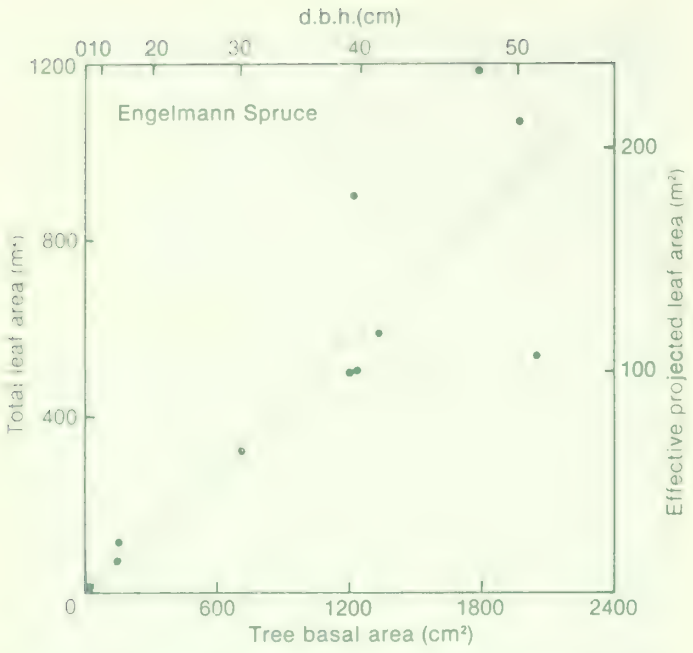

Figure 1.—Effective projected and total leaf (needle) area of Engelmann spruce as a function of tree basal area and d.b.h. See table 2 for appropriate regression equations.

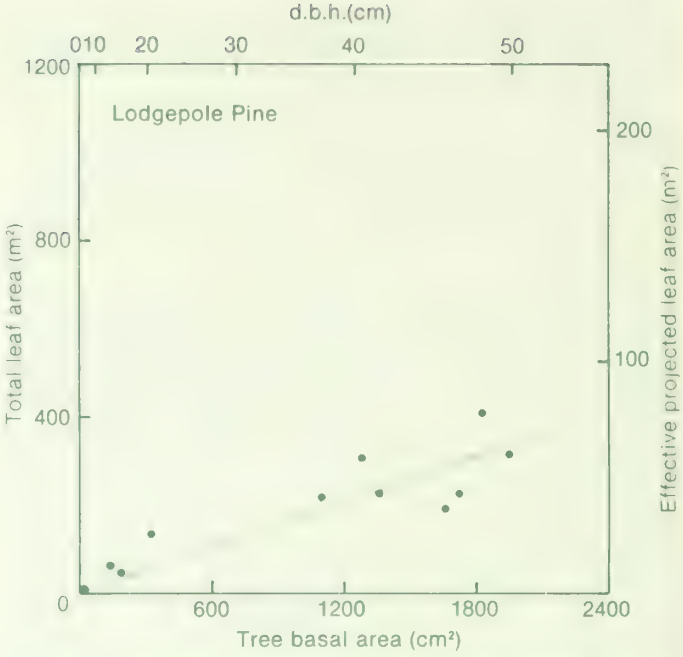

Figure 3.—Effective projected and total leaf (needle) area of lodgepole pine as a function of tree basal area and d.b.h. See table 2 for appropriate regression equations.

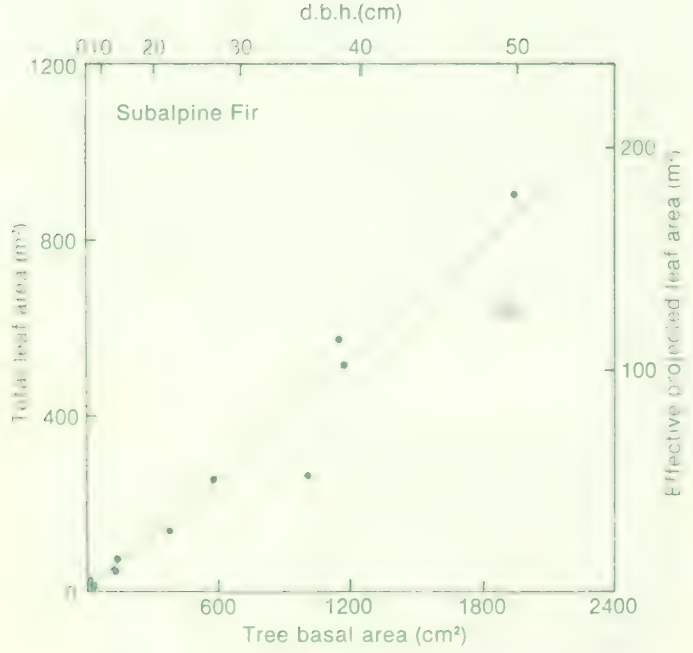

Figure 2.—Effective projected and total leaf (needle) area of subalpine fir as a function of tree basal area and d.b.h. See table 2 for appropriate regression equations.

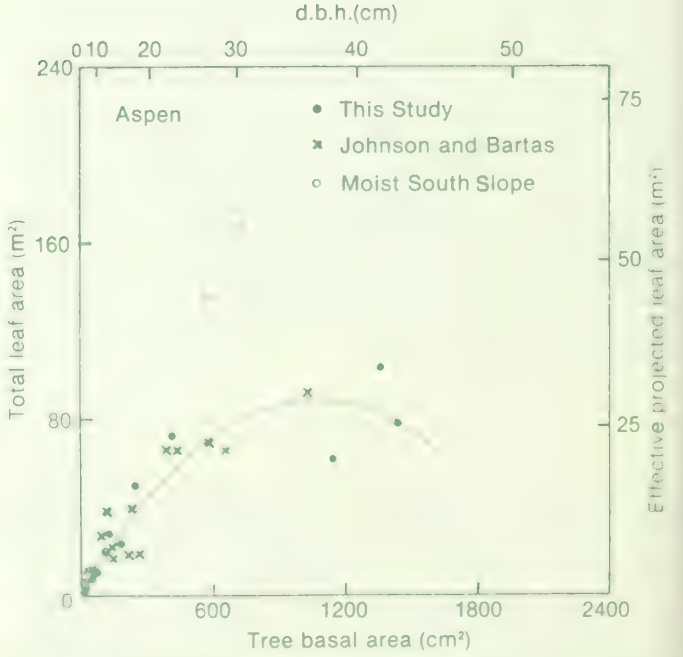

Figure 4.—Effective projected and total leaf area of aspen as a function of tree basal area and d.b.h. See table 2 for appropriate regression equations. Regression equations are based upon the combined data of this study and Johnston and Bartos (1977), but excluding the two trees located on the moist south slope.

Table 2.—Effective projected leaf area (EPLA) or total leaf area (TLA) as a function of basal area per tree (BA) or d.b.h. Leaf area is in m^2, BA is in cm^2, and d.b.h. is in cm

Species	Equation	R^2 [a]	Standard error of estimate
Engelmann spruce	TLA = 0.483 BA TLA = 0.379 d.b.h.^{2} EPLA = 0.0958 BA EPLA = 0.0752 d.b.h.^{2}	0.904	178.33
Subalpine fir	TLA = 0.437 BA TLA = 0.343 d.b.h.^{2} EPLA = 0.0867 BA EPLA = 0.0681 d.b.h.^{2}	0.975	60.30
Lodgepole pine	TLA = 0.174 BA TLA = 0.137 d.b.h.^{2} EPLA = 0.0331 BA EPLA = 0.0261 d.b.h.^{2}	0.930	55.99
Aspen	TLA = 0.168 BA $-$0.0000787 BA^2 TLA = 0.132 d.b.h.^{2} $-$0.0000486 d.b.h.^{4} EPLA = 0.0535 BA $-$0.0000251 BA^2 EPLA = 0.0420 d.b.h.^{2} $-$0.0000155 d.b.h.^{4}	0.944	11.15

[a] *Although the coefficient of determination* (R^2) *for a zero-intercept model is technically undefined, it is included here for comparison of equations.*

Table 3.—Effective projected leaf area (EPLA) or total leaf area (TLA) as a function of tree height (TH). Leaf area is in m^2, TA is in m

Species	Equation	R^2 [a]	Standard error of estimate
Engelmann spruce	EPLA = 0.1931 TH^2 TLA = 0.975 TH^2	0.869	208.2
Subalpine fir	EPLA = $-$2.292 TH + 0.2701 TH^2 TLA = $-$11.574 TH + 1.364 TH^2	0.974	64.39
Lodgepole pine	EPLA = 0.0791 TH^2 TLA = 0.416 TH^2	0.920	59.73
Aspen	EPLA = 0.996 TH TLA = 3.126 TH	0.867	16.80

[a] *Although the coefficient of determination* (R^2) *for a zero-intercept model is technically undefined, it is included here for comparison of equations.*

Table 4.—Effective projected leaf area index (EPLAI) or total leaf area index (TLAI) as a function of stand basal area (SBA) and tree basal area (BA). Leaf area index is in $m^2 \cdot m^{-2}$, SBA is in $m^2 \cdot ha^{-1}$, and BA is in cm^2

Species	Equation
Engelmann spruce	EPLAI = 0.0958 SBA TLAI = 0.483 SBA
Subalpine fir	EPLAI = 0.0867 SBA TLAI = 0.437 SBA
Lodgepole pine	EPLAI = 0.0331 SBA TLAI = 0.174 SBA
Aspen	EPLAI = 0.0535 SBA $-$0.0000251 SBA $\cdot$ BA TLAI = 0.168 SBA $-$0.0000787 SBA $\cdot$ BA

Table 5.—Effective projected leaf area index (EPLAI) or total leaf area index (TLAI) as a function of stand basal area (SBA) and tree basal area (BA). Leaf area index is in $ft^2 \cdot ft^{-2}$, SBA is in $ft^2 \cdot acre^{-1}$, and BA is in ft^2

Species	Equation
Engelmann spruce	EPLAI = 0.0220 SBA TLAI = 0.111 SBA
Subalpine fir	EPLAI = 0.0199 SBA TLAI = 0.100 SBA
Lodgepole pine	EPLAI = 0.00760 SBA TLAI = 0.0399 SBA
Aspen	EPLAI = 0.0123 SBA $-$ 0.00535 SBA $\cdot$ BA TLAI = 0.0386 SBA $-$ 0.0168 SBA $\cdot$ BA

(1981) demonstrated that leaf area above any level in the crown may be estimated by measuring sapwood area at the base of the level. Because sapwood area and total cross-sectional area are well correlated, suitable estimates of leaf area using nondestructive diameter measurements are possible.

Values of total leaf area index for the subalpine tree species examined here agree well with those observed in other parts of North America. The maximum basal area of Engelmann spruce-subalpine fir stands is about 90 $m^2 \cdot ha^{-1}$; typically stands are composed of 90% spruce and 10% fir.[2] Total leaf area of these stands is 40 to 45 $m^2 \cdot m^{-2}$ (fig. 5). Gholz et al. (1976) reported total leaf areas of 42 $m^2 \cdot m^{-2}$ for mature stands of western hemlock and silver fir stands in the western Oregon Cascades.

In contrast, the maximum stand basal area of lodgepole pine in the central Rocky Mountains is about 70 $m^2 \cdot ha^{-1}$.[2] The total leaf area index of these stands is about 12 $m^2 \cdot m^{-2}$ (fig. 5), compared with values of 8-9 $m^2 \cdot m^{-2}$ for dry western hemlock and Douglas-fir sites (Gholz et al. 1976). Maximum leaf area indices for aspen were about 13 $m^2 \cdot m^{-2}$, and most stands were no higher than 9-12 $m^2 \cdot m^{-2}$ (fig. 6).[3] Total leaf area indices for eastern deciduous forests are typically 8 to 12 $m^2 \cdot m^{-2}$ (Whittaker 1966).

[2]*Personal communication with Robert R. Alexander, Chief Silviculturist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.*

[3]*Personal communication with Wayne D. Shepperd, Research Silviculturist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.*

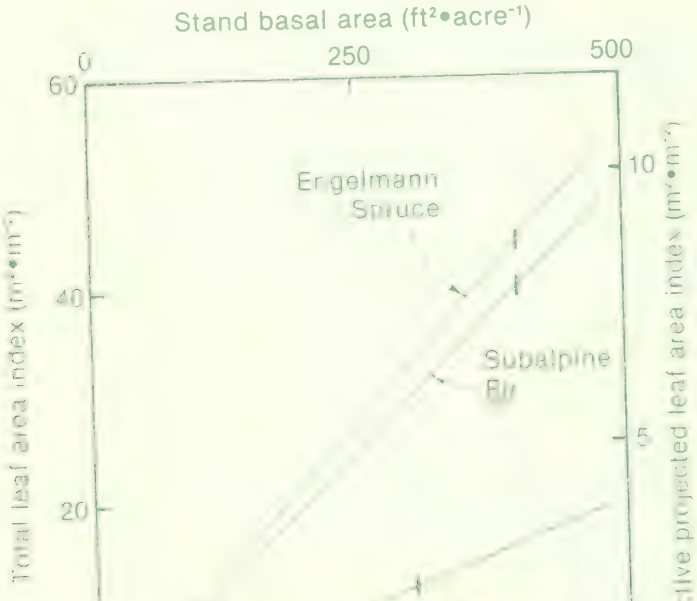

Figure 5.—Effective projected and total leaf area index as a function of stand basal area. Vertical slashes indicate normal upper limit for basal area of each species in the central Rocky Mountains.

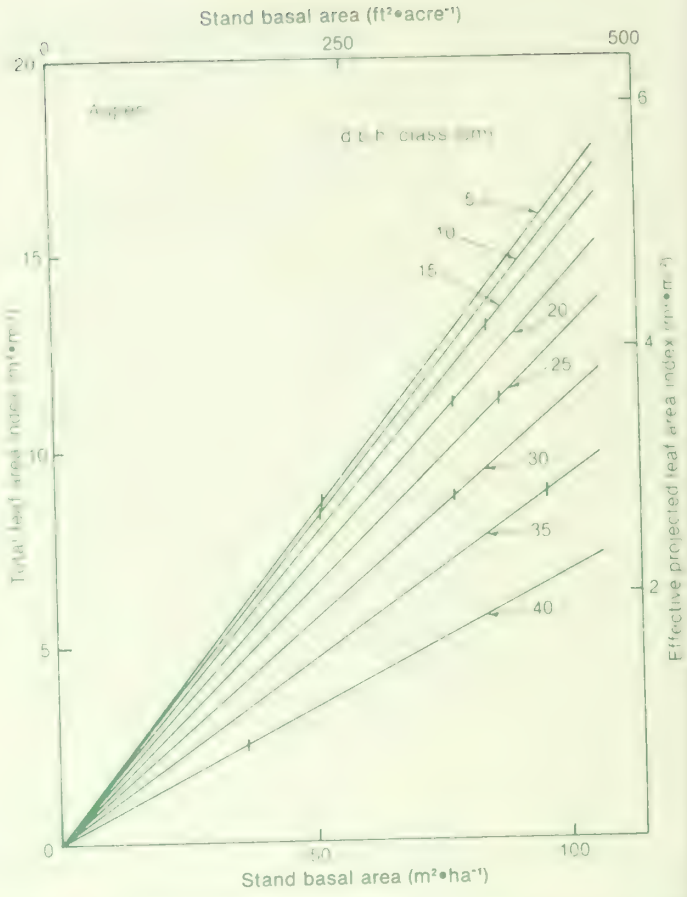

Figure 6.—Effective projected and total leaf area index of aspen as a function of stand basal area and tree diameter. Vertical slashes indicate upper limit for basal area by diameter in a large number of Colorado aspen stands (personal communication with Wayne D. Shepperd, Research Silviculturist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.).

In some coniferous species (e.g., loblolly pine), needles persist for only 2 or 3 years. For such species, the total amount of foliage may vary considerably through a given year as a result of needle senescence and growth of new needles. For the three subalpine conifers studied here, needles persist for 7-20 years. Therefore, changes in needle area caused by seasonal variations in needle senescence and growth are masked by the large total amount of foliage. For aspen, however, the equations given above are for trees with fully expanded foliage. During the several-week period of leaf expansion in early June, leaf areas are below those predicted by the equations.

Species differences in leaf area index may affect understory vegetation and processes. For spruce-fir stands having high basal areas, little solar or visible radiation penetrates through the canopy to the forest floor. Consequently, only the most shade-tolerant tree species can become established in the understory. While the forest floor is often moist in such stands, low light intensity limits growth of ground cover species. Furthermore, evaporation from the soil surface is probably low because little solar energy is available.

In lodgepole pine and aspen stands, solar and visible radiation intensity beneath the canopy is greater than in spruce-fir stands. However, considerable differences in environmental conditions may exist at the forest floor beneath pine and aspen stands, even when the projected leaf area indices of the overstory are equal. Pine stands in the central Rocky Mountains are often characterized by dry litter and minimal understory vegetation. Dry litter and low amounts of vegetation may indicate high rate of evaporation at the soil surface, as a result of substantial shortwave radiation reaching the forest floor.

Similar visible and shortwave radiation probably reaches the forest floor beneath aspen stands, although the thin leaf structure of aspen may result in higher radiation levels beneath the canopy because of transmission through the leaves. Leaf orientation also may favor less interception of radiation by aspen leaves than by pine needles, particularly at solar noon if leaves tend to be oriented vertically. Aspen stands are almost always characterized by more dense understory vegetation, including conifer regeneration if seed sources are available. Dense understory vegetation may result from plant establishment early in the growing season, when decomposing litter and high soil surface moisture supplies create good seedbed conditions for germination. Furthermore, the aspen overstory canopy often leafs out after the understory begins to grow, thus giving the understory vegetation an early environmental advantage it would not have beneath a conifer canopy.

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Needle area of Engelmann spruce, subalpine fir, and lodgepole pine and leaf area of aspen are predicted from d.b.h. or tree height. Leaf area index can be calculated from stand basal area.

Keywords: Needle area, leaf area index, d.b.h., basal area, tree height, Engelmann spruce, subalpine fir, lodgepole pine, aspen

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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The Economic Value of Improved Fuels and Fire Behavior Information

Stephen M. Barrager
David Cohan
and
Peter J. Roussopoulos

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Research Paper RM-239
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

ABSTRACT

An analysis of two routine fire management decisions on the Mount Hood National Forest provided insights into the appropriate expenditure levels for improving fuels and fire behavior information bases. In formulating the annual fire management budget request, improved information on fuel types is worth about one cent per acre per year, while the value of perfect fire intensity prediction is between one and five cents per acre per year. For complex decisions among alternative postharvest fuel treatments, reliable postharvest fuel loading estimates may be worth up to $800 for a 25-acre site.

ACKNOWLEDGMENTS

William Waterbury, Gordon Schmidt, and Jack Neuman of the Mount Hood National Forest consulted on local site conditions and fire management practices. Their help and cooperation were essential to the success of the project. John Dell of the USDA Forest Service, Pacific Northwest Region, and Wayne Maxwell of the Pacific Northwest Forest and Range Experiment Station also provided valuable assistance.

USDA Forest Service
Research Paper RM-239

September 1982

The Economic Value of Improved Fuels and Fire Behavior Information[1]

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The Economic Value of Improved Fuels and Fire Behavior Information

Stephen M. Barrager, David Cohan, and Peter J. Roussopoulos

MANAGEMENT IMPLICATIONS

Many resource management decisions are based, in part, on estimates of forest fuel quantity, type, and condition. Existing and anticipated fuel conditions play a key role in predicting future wildfire activity and attendant impacts on management programs and resource outputs. Presumably, better information about fuels and fire behavior would enable land managers to make better fire management decisions and, thereby, improve the efficiency of fire management programs.

Improving information on fuels and fire behavior can be costly. It is necessary to balance the expected benefits with the costs of gathering or developing improved information. The value of new information depends upon many factors, the most important of which are the current level of information, the likelihood that new information will change decisions and, thereby, alter management actions, and the reduction in costs or losses accompanying a decision change. This report describes a quantitative analysis of the economic value of improved fuels and fire behavior information to fire managers and discusses the balancing of the economic value with the costs of such information. Although the specific models developed in this analysis are unique to the decisions and areas described, the general analysis approach can be useful in a large variety of resource management decision situations.

The analysis presented here spans the range of resolution requirements for fuels and fire behavior information by addressing the value of such information in the context of two decisions on the Mount Hood National Forest:

1. Formulating the annual fire management budget request at the national forest level or its equivalent—What is the most appropriate annual expenditure for wildfire protection on the forest?
2. A site-specific, fuel treatment decision—What is the most appropriate fuel treatment following harvest of a 25-acre stand? Alternatives include no treatment, prescribed burn, and intensive mechanical treatment.

In the analysis of each decision, the objective was to minimize management (or treatment) costs plus expected net resource value changes due to fire. No attempt was made to evaluate the ancillary benefits of wildland fuel information for making resource management decisions (e.g., site preparation, wildlife habitat management, and watershed management).

Budget Analysis Results

Over a wide range of cases, the expected value of perfect information on the distribution of fuel types for this decision was on the order of one cent per acre per year, which corresponds to about $10,000 per year for the entire Mount Hood National Forest. Note that this amount is the value of perfect information; that is, information that completely eliminates uncertainty. As such, it should be considered an upper bound on the value of new fuels information to the Mount Hood National Forest in the context of fire management budget decisions. This suggests that any forest-wide fuels inventory effort would not be economically justified for developing the annual fire management budget request. Funds invested in the development of an improved system of records-keeping (applicable to many national forests) to better utilize information already available (e.g., from timber stand surveys, fuel treatment activities, and other resource management activities) may be of greater value.

The expected value of perfect fire intensity predictions for wildfires was typically in the range of one to five cents per acre per year. While this is probably insufficient to merit any forest-specific research or detailed data gathering, it could justify continued research toward the development of improved models of fire behavior that would be of use on a number of forests.

A simple decision tree analysis was used to investigate the value of adding new fuel models to the existing set; that is, of providing a set of stylized fuel models with greater resolution. An additional model only rarely resulted in a changed decision; as a result, its availability had little value. This finding suggests that the resolution provided by the stylized fuel models now available is probably appropriate for formulating fire management budget level requests and may be appropriate for other forest-level fire management decisions.

Fuel Treatment Decision Results

Results of the analysis showed that for a wide range of assumptions the "no-treatment" alternative (which actually involves a small amount of hand treatment) was dominant, which leads to two possible conclusions:

1. Direct resource benefits of fuel (residue) treatment (such as for enhancing watershed, wildlife, or other resource values) are considerably in excess of those quantified in this analysis (i.e., the reduction of future wildfire losses).

2. Much more treatment activity is being carried out than is economically justified.

If the first conclusion is correct and some type of treatment must be carried out, the choice is between the prescribed burn alternative and the more costly but less uncertain intensive treatment.

Using the most likely scenarios, when the no-treatment alternative is inappropriate, the expected value of perfect information on postharvest fuel loading was approximately $300 to $800 for the 25-acre site (or $12 to $32 per acre). Information that could be expected to reduce uncertainty (perhaps reducing the variance of the probability distribution on the loading of fine fuels by 50-70%) would be worth $100 to $400 ($4 to $16 per acre). Accounting for all costs, this suggests that in many cases it would be worthwhile to invest one or two person-days in developing an improved estimate of postharvest fuel loading before making the final treatment decision.

Recommendations Based on the Mount Hood Analysis

1. For broad fire management planning and budgeting purposes, forest supervisors should consider forest-wide fuels inventory or fuels information management options which cost no more than two cents per acre annually.
2. The resolution provided by the sets of stylized fuel models now available should be considered adequate for evaluating alternative fire management budget levels.
3. Continued research to provide better understanding of fire behavior and budget effectiveness (the relationship between fire management activities and fire losses) appears to be justified.
4. Expensive fuel treatment following harvest does not seem to be justified in cases similar to that examined here if fire hazard reduction is the principal objective. More careful thought should be given to the no-treatment alternative in such cases.
5. Where other resource management objectives dominate the residue treatment decision (e.g., site preparation), and where broadcast burning is likely to be a good alternative but significant resource values may be sensitive to burning, it is probably worth investing on the order of one or two person-days per 25-acre cut-block in the improvement of the fuel information base prior to making the final treatment decision.

The above recommendations are applicable only in the context of the two types of decisions addressed in this analysis. They consider only the value of fuel and fire behavior information for evaluating the expected fire-related impacts of decision alternatives on resource outputs, and they are based on the current state of information available to Mount Hood National Forest managers, as related to the authors. These results may not be applicable to other types of fire management decisions or to management situations where the current state of information is substantially different from that described on the Mount Hood National Forest.

INTRODUCTION

Managers at all levels within the Forest Service and other land management agencies require estimates of fire behavior and expected losses or benefits from fire. At the highest levels, land use policy is affected by perceived fire hazards, as is fire protection planning, which is based on estimates of fire occurrence, behavior, and attendant damages or benefits. At the lower levels, tactical fire suppression decisions and site-specific fuel treatment choices utilize more precise fire behavior estimates. Information about the amount and character of wildland fuels plays a noteworthy role in all these decisions. Wildland fuels include aggregations of twigs, branches, stems, foliage, detritus, and other living and dead vegetative materials that occur on wildlands, either through natural processes or as a result of human activities. Fuel information quality affects the manager's ability to predict fire behavior and estimate fire effects, whether beneficial or detrimental. Just what quality of information is needed for various management activities, in terms of accuracy and resolution, is not well known.

This report describes a case study to determine the economic value of improved information about the quantity and properties of wildland fuels. Presumably, better fuels information would enable forest managers to improve the efficiency of fire management programs. The value of improved fuels information depends upon many factors, the most important of which are the current level of information, the probability that new information will result in changed decisions, and the expected change in costs and resource values resulting from those decision changes. This case study explicitly addresses these factors and estimates the maximum value of new fuels information on a dollar-per-acre basis.

The area chosen for this case study comprises two ranger districts of the Mount Hood National Forest, Clackamas and Estacada, covering about 400,000 acres of the western slope of the Cascade Mountain Range near Portland, Oreg. The areas are heavily forested with commercially valuable Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). About $6,000,000 worth of commercial sawtimber is harvested from the two districts each year (600 acres). The fuel treatment and fire suppression budget for the districts was $743,000 in 1978, and wildfires burned an average of about 200 acres each year from 1970 to 1978. The resulting annual fire losses averaged about $1,200 per acre or $240,000 per year for the two districts.

This case study concentrated on determining the value of fuels information in the context of two clearly recognizable decisions:

1. The forest-level, annual, presuppression fire management budget request decision.
2. A site-specific, postharvest fuel treatment decision.

Based on each of these decisions, managers allocate a substantial amount of money annually in an effort to reduce fire losses. The alternatives, outcome measures, and major uncertainties for each decision are summarized in table 1.

Fuel information is useful in the budget request decision as an aid in estimating fire hazard and the potential effectiveness of money spent preventing and managing wildfires. Presumably, the budget will be too small if the expected fire hazard is underestimated and too large if it is overestimated. Fuel information is useful in the site-specific, fuel treatment decision as an aid in estimating the effects of a prescribed fire as well as the postharvest fire hazards associated with different treatment methods.

These two decision classes span most of the range of precision requirements for fuel-related fund allocation decisions at the forest level. While the budget decision is large, it is made only once a year. The annual budget for fire prevention, presuppression, and initial attack was about $266,000 in 1978 for the Clackamas and Estacada districts. (An additional $477,000 was budgeted for treating the fuel associated with current and past logging operations. The bulk of these latter funds is from timber sale collections.) The site-specific, fuel treatment decision is much smaller, involving expenditures from $2,500 to $32,500 for a 25-acre site, depending upon the treatment chosen. However, roughly 25 fuel treatment decisions of this type are made each year on the Clackamas and Estacada districts.

The object of this report is to provide insight into the role of fuel information and its approximate value within two specific decision contexts on the Mount Hood National Forest—not to derive a precise single number that expresses the total value of additional fuel information. Details of the two analyses are presented in separate sections, following an explanation of the analytical approach used to estimate potential information value.

ANALYTICAL APPROACH

The economic value of wildland fuel information is calculated by estimating the impact that improved information has on fire losses or benefits and management costs. This section contains an overview of the forest level budget decision and how it might be affected by fuel information. An illustrative calculation of the expected value of perfect information (EVPI) is also included in this section to provide an understanding of how the economic value of information is determined. A more practical treatment of the budget request decision and actual calculations for the Mount Hood case study are presented subsequently.

Ideally, the fire management budget is established at a level that minimizes the combined management costs and net resource value changes caused by wildfire (NVC). In this formulation, positive NVC values represent net resource damages, while negative values represent net benefits. The historical development of this criterion, along with other fire management objectives, is traced by Gorte and Gorte (1979). Affected values may include wildlife, watershed, and recreation values, as well as timber values and improvements. The optimal budget level is illustrated in figure 1. Identifying the optimal budget would be straightforward if the relationship between presuppression expenditures and suppression costs plus NVC were known as indicated in the figure. The budget decision is complicated, however, by the fact that this relationship is highly uncertain. The major contributors to this uncertainty are the number and location of fires in the coming year, fuel conditions, weather, fire behavior, fire effects, and the effectiveness of presuppression expenditures (budget effectiveness).

The object of this case study is to estimate the economic value of reducing several of these uncertainties by improving information available to the decisionmaker. To illustrate the methodology, suppose that the only uncertainties are fuel conditions and budget effectiveness. Suppose, also, that the budget decision is simplified to two distinct alternatives: increase the budget by 10% or maintain the current level. This decision, the subsequent uncertainties, and the outcomes (cost plus NVC) are diagramed in decision-tree form in figure 2. As indicated in the diagram, there are two

Table 1.—Summary of decisions addressed in this study

	Decision alternatives	Outcome measures	Major uncertainties
Annual fire management budget request decision	Continue current budget level Increase budget Decrease budget	Fire management costs Fire effects (resource value changes from wildfires)	Aggregate fuel characteristics Fire intensities given fuel characteristics Budget effectiveness
Fuel treatment decision	No treatment Prescribed burn YUM 6 × 6[1]	Posttreatment fire hazard Losses to residual stand	Postharvest fuel characteristics Prescribed fire intensity Treatment effects (fuel reduction and damage to residual stand)

[1] *YUM 6 × 6 stands for Yarding Unmerchantable Material—all material exceeding 6 feet long by 6 inches in diameter.*

possible fuel situations: 100% of the area is represented by stylized fuel model 10 or 100% of the area is equivalent to model 8. These stylized fuel models are described by Albini (1976). Model 8 (closed timber litter) implies a fuel loading of about 15 tons per acre (fine fuels), while model 10 (timber litter plus understory) represents a loading of about 30 tons per acre.

Assume that the entire planning unit is covered with the same fuelbed and that there is a probability of 0.5 that the fuel is described by fuel model 8. If the increase-budget alternative is selected, and model 10 turns out to be most representative of the fuel, there is an equal chance that the budget increase will result in a 10% or 20% reduction in the number of escaped fires. For the same alternative, model 8 implies an equal probability of a 10% decrease or no change in escaped fires.

Hypothetical outcome costs are broken down into three classes—presuppression, suppression, and NVC—and are itemized at the tip of each branch. Suppression costs are proportional to NVC.

Tracing one path through the decision tree, the upper path denotes a choice to increase the budget by 10%, the fuelbed is most closely characterized by model 10, and the effect of the 10% budget increase is 20% reduction in escaped fires. This scenario results in $110,000 in presuppression costs, $40,000 in suppression costs, and NVC of $120,000. The probability that this outcome will occur is 0.25 if the increase-budget alternative is chosen.

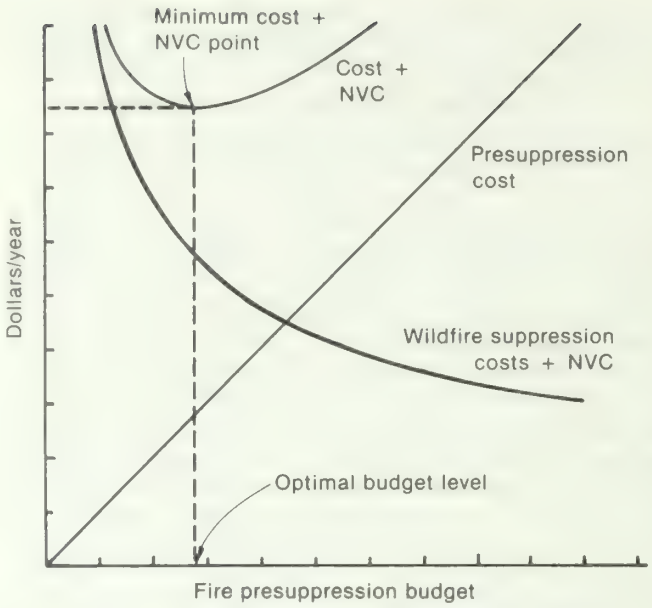
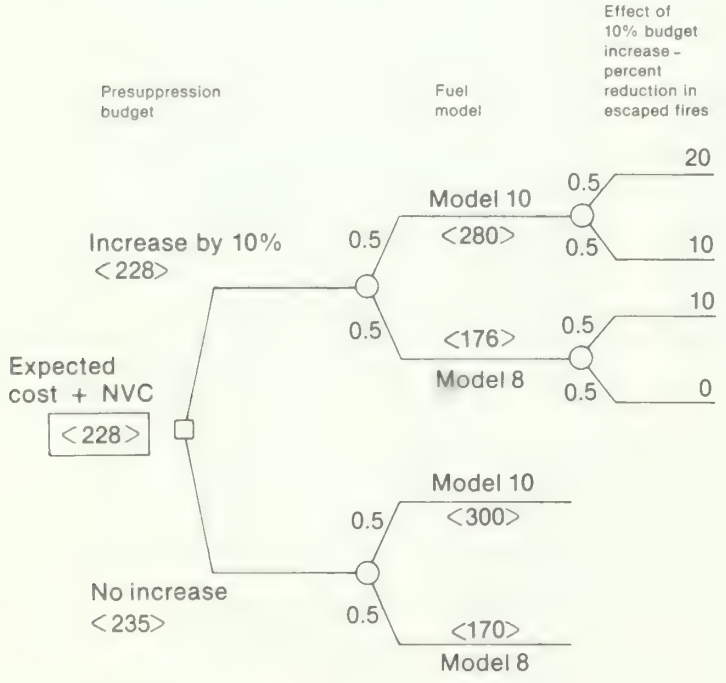


Figure 1.—Determination of the optimal budget level.

Given the uncertainty and cost structure of the example, the expected cost plus NVC is lower for the increase-budget option—$228,000 versus $235,000 for the no-increase option. (The term "expected cost plus NVC" is used here in the statistical sense. It is the sum of the probability of each outcome times its overall cost; e.g., 235 = 0.5 × 300 + 0.5 × 170.) Assuming that minimizing the expected net cost is the basis for



Probability of this outcome	Presuppression costs ($1000)	Suppression costs ($1000)	Net resource value change (NVC) ($1000)	Total cost + NVC ($1000)
0.25	$110	$40	$120	$270
0.25	110	45	135	290
0.25	110	18	45	173
0.25	110	20	50	180
0.5	100	50	150	300
0.5	100	20	50	170

□ Denotes a decision
○ Denotes the resolution of uncertainty; a probability node
< > Denotes expected value

Figure 2.—Presuppression budget decision.

the decision, the increased budget alternative is preferred in this example.

What would it be worth to know precisely whether model 8 or model 10 is the right choice before making the budget decision? In other words, how much should we be willing to pay a clairvoyant to look into a crystal ball and tell us which fuel model is appropriate? By a simple example, we can calculate the expected value of the information by rearranging the tree to represent the sequence of events when fuels information is known before the decision is made. This situation is diagramed in figure 3. The model 10 probability is still 0.5 from our perspective, but at the time the decision is made, it is either 1 or 0, depending on whether the clairvoyant says "8" or "10." If the clairvoyant says that model 8 is appropriate, we would change our choice and maintain the current budget, because under these circumstances the expected cost plus NVC is lower ($170,000 rather than $176,000) at the current budget level. If we knew for sure that model 10 was appropriate, we would increase the budget. The expected cost for this choice is $280,000. The arrows in the diagram denote the lowest cost alternative at each decision node.

We should be willing to pay up to $3,000 for perfect information on fuel conditions before making the budget decision. This amount is the difference between the expected cost with prior information from figure 2 ($228,000) and the expected cost with perfect information from figure 3 ($225,000).

Another way of looking at this is illustrated in figure 4. Here the decision tree is redrawn to make it ap-

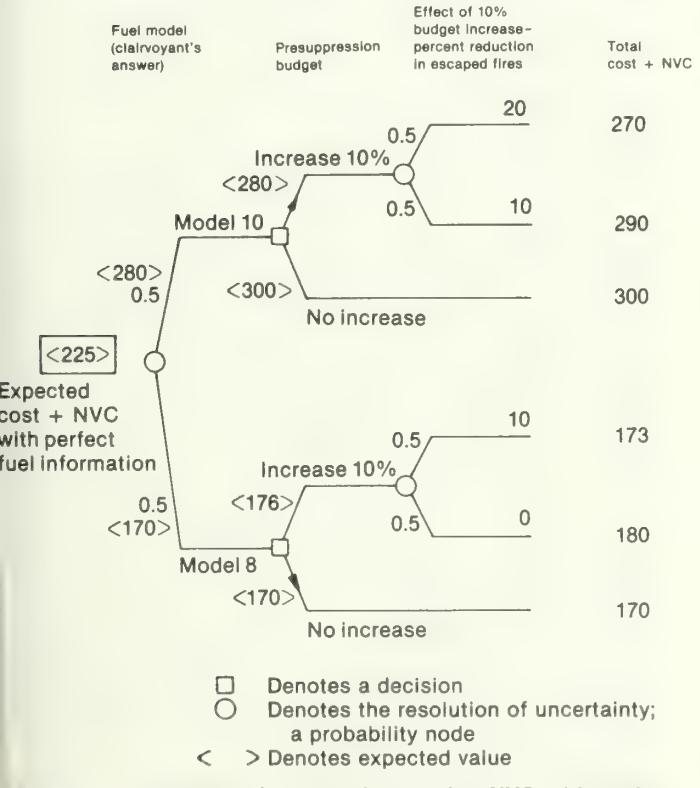


Figure 3.—Calculation of expected cost plus NVC with perfect fuel information.

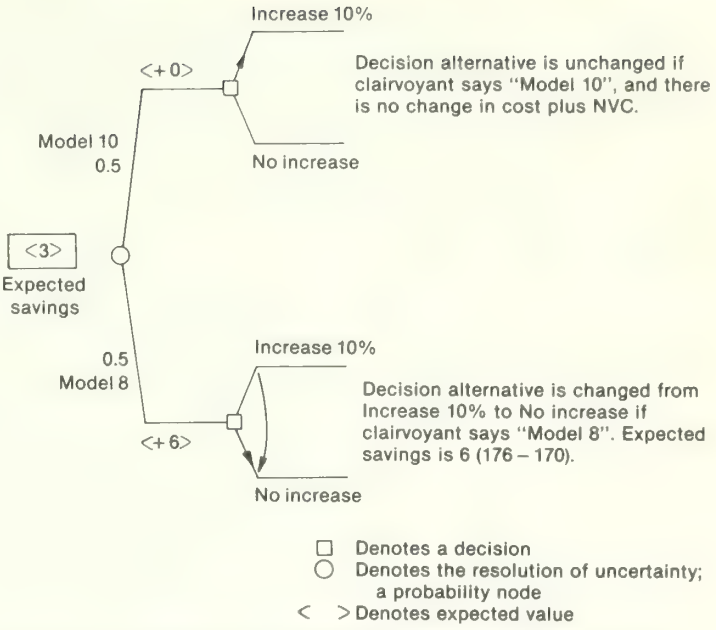

Increase 10%
<+0>
Decision alternative is unchanged if clairvoyant says "Model 10", and there is no change in cost plus NVC.
Model 10
0.5
No increase
<3>
Expected savings
0.5
Model 8
Increase 10%
Decision alternative is changed from Increase 10% to No increase if clairvoyant says "Model 8". Expected savings is 6 (176 – 170).
<+6>
No increase
Denotes a decision
Denotes the resolution of uncertainty; a probability node
< > Denotes expected value

Figure 4.—Calculation of expected savings from perfect information.

parent how the expected cost savings result from the clairvoyant's perfect information. Briefly, if the clairvoyant says "model 8," our choice is changed from an increase of 10% to no increase and the resulting expected savings are $6,000 (176-170). If the clairvoyant says "model 10," the decision does not change and the expected cost plus NVC is unchanged. The probability that the clairvoyant will say "model 8" and save us $6,000 is 0.5; therefore, the expected savings is 0.5 times $6,000 or $3,000, which matches the previous value of perfect information calculation. For further discussion of this procedure, refer to Howard (1966) and North (1968).

Although perfect information is not attainable in practice, the expected value of perfect information is useful because it provides an upper bound on what one should be willing to pay for any level of fuel information in the context of a single decision or class of decisions. The perfect information concepts are used in the following sections to provide insight into the value of fuel inventory or modeling efforts. The value of information is estimated under a broad range of conditions to test the utility of the estimates in varying field situations.

THE FIRE MANAGEMENT BUDGET REQUEST

This section examines in detail the decision made by the management of a national forest in requesting a budget level for fire protection activities. The specific decision evaluated in this section of the case study is the overall fire management budget level for the Clackamas and Estacada districts of the Mount Hood National Forest. Some insights were also gained concerning the allocation of the overall budget among the various fire management activities. Although the

details reflect these two districts uniquely, many of the insights and conclusions are applicable to the entire Mount Hood National Forest and, in fact, to many national forests.

The Decision

Nature of the Decision

Each year every national forest supervisor must submit a budget request for the fiscal year beginning 2 years hence. Typically, work plans for individual districts are aggregated by forest staff to produce tentative budget requests by management activity. These are reviewed, modified, and consolidated by the forest supervisor to produce a fully specified budget request for the forest, which is subsequently reviewed and frequently modified by higher levels of the Forest Service, the Department of Agriculture, the Office of Management and Budget, the President, and Congress.

The fire management component of the annual budget request identifies funds allocated to wildfire prevention, detection, maintenance of initial attack forces, maintenance of air support forces, and fuel management. Wildfire suppression costs have generally been accounted for separately. This case study will focus on the decision made by the individual national forest staff in attempting to formulate and justify an optimal budget request for wildfire protection activities.

Budget Optimization

The optimization of fire management expenditures has been a subject of continued practical and academic interest throughout the history of organized wildfire protection in the United States (Pyne 1981). The theoretical development and application of economic models and criteria related to this task are discussed by Gorte and Gorte (1979). Mills[4] examines and compares three approaches to identifying financially optimum levels of fire protection for wildland resources—cost + NVC, benefit/cost ratios, and present net worth.

Since enactment of the Renewable Resources Planning Act (RPA) and the National Forest Management Act (NFMA), there has been a marked upsweep of interest in determining the economic efficiency of fire management programs. Prompted by escalating fire management costs during the early 1970's, the Office of Management and Budget asked the Forest Service in 1975 to account for increasing expenditures and to identify which fire management practices are best in terms of costs and results.[5] The Forest Service response (U.S. Department of Agriculture, Forest Service 1977) documented real program cost trends over the period 1965 to 1975, but those preparing the response were unable to identify which practices were best. As a result, the Forest Service initiated a study to analyze the economic efficiency of fire management programs on six national forests representing a range of fire management situations throughout the nation (Schweitzer et al. 1982). Results indicated that the initial attack and aviation operation budgets on four of the six forests should be reduced by 20% in order to minimize expected cost plus NVC. Similar methods were later extended to a study of 41 national forests (U.S. Department of Agriculture, Forest Service 1980a), where results were aggregated nationally. The latter analysis indicated that minimum cost plus NVC for Fiscal Year 1980 could be achieved by increasing the National Forest System's fire protection budget by 13-20% over the FY 1979 level. Methods and criteria from both of these studies have been incorporated in a Forest Service Handbook procedure for analyzing fire management programs within the context of forest planning (U.S. Department of Agriculture, Forest Service 1980b). Mills (1979) describes ongoing research to refine these procedures and further develop management guidelines for economic evaluation of fire management practices.

The present analysis of the Mount Hood National Forest budget decision focuses on determining the expected value of improved information for optimizing the fire management budget request; it is not concerned with actually identifying the optimum budget level. Analytical models and procedures, therefore, differ somewhat from those used in previous fire management budget analyses.

Definition of Outcomes

Under the cost-plus-NVC criterion for determining the optimal budget level the objective is to minimize the sum of fire management costs and NVC caused by the fires and fire-associated activities. The cost side is reasonably clear. For a given year, uncertainty is introduced only by the possible range of expenditures for fire suppression. The resource value changes are more difficult to determine. Most easily measured are the timber value changes and costs of rehabilitation. Less easily quantified are watershed, recreation potential, visual amenities, and other resource values. The fact that many of these benefits or damages are often difficult to measure and equally difficult to put into economic terms does not lessen the need for considering them when analyzing forest management decisions (Daniel and Zube 1979).

One way to represent the decision is outlined in figure 5. The decision itself is shown at the bottom of the figure, while important uncertainties are shown at the left. The decision alternative selected, the uncertain factors, and the forest system interact to result in a set of outcomes, which are the factors a decisionmaker would like to know to evaluate the consequences

[4] *Mills, Thomas J. Calculation of financial return and determination of budget levels for fire protection programs. (Manuscript in preparation). U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.*

[5] *Lynn, James T. 1975. Letter to Honorable Earl Butz, Secretary of Agriculture. April 15, 1975. Executive Office of the President, Office of Management and Budget, Washington, D.C.*

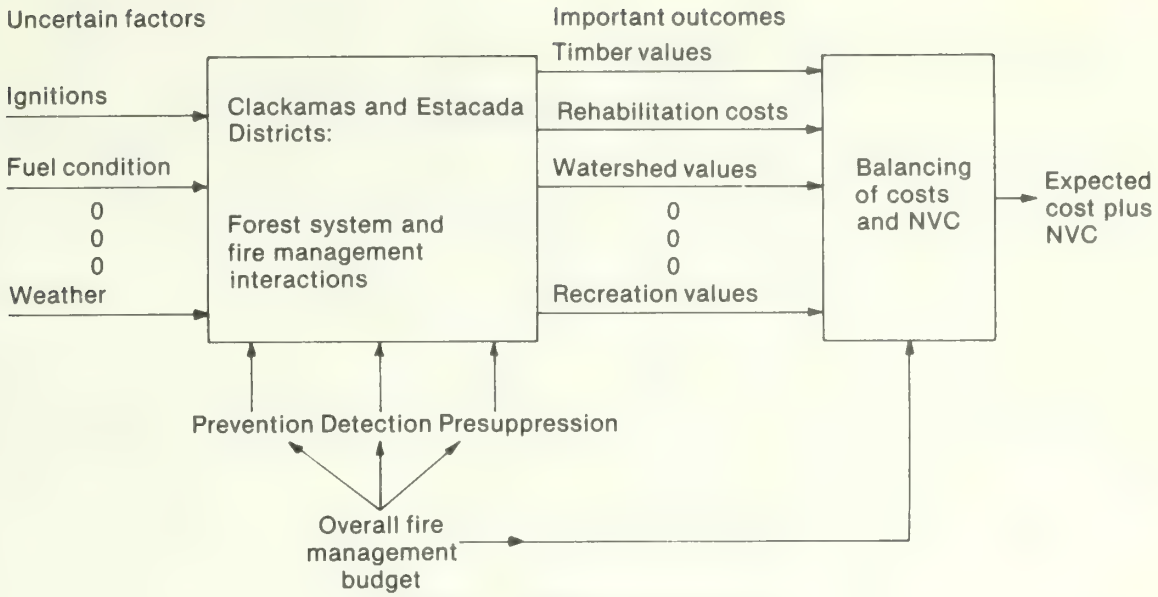


Figure 5.—Budget decision outline.

of the decision. The outcomes are assigned values and are added with the management costs to produce an expected cost plus NVC.

Representation of Uncertain Factors

Preliminary sensitivity analyses identified fuel conditions and the resulting fire behavior as among the most critical uncertain factors affecting the budget level decision. Uncertainty in fire effects and resource values was also important. These elements were treated parametrically, in an effort to model and analyze the budget request decision. This approach allows comparison of decision alternatives over a wide range of possible values. Uncertainty in the effectiveness of budget expenditures was also important and was treated separately. (Effectiveness is measured as the reduction in fire losses associated with an increase in the budget.) Part of the uncertainty in predicting fire intensity reflects uncertainty in future weather conditions. However, the aggregate nature of the budget request decision, involving broad areas over a full fire season, allows adequate representation of weather variations using archived local fire weather observations (Furman and Brink 1975). Similarly, local fire occurrence data (Roussopoulos et al. 1980) provide a useful means of representing variations in annual fire occurrence patterns.

Fuel Conditions.—For modeling a decision at the aggregate level of the overall fire management budget, the stylized fuel models described by Albini (1976) provided a starting point to represent fuel loading and characteristics. A simple analysis, described later in this section, yielded estimates of the value of developing a more detailed set of stylized fuel models (i.e., more models, thus providing greater resolution). Mount Hood National Forest fuels and fire management staff felt that 4 of the 13 available models will adequately describe the fuels conditions of the Clackamas and Estacada districts. These were model 10 (timber litter and understory), model 8 (timber litter), model 13 (heavy slash), and model 12 (medium slash). Fuel and fire specialists on the Mount Hood National Forest were uncertain as to how the total area should be allocated among the four stylized models. The uncertainty was reflected in varying estimates by Mount Hood staff of the fraction of the total case study area that should be represented by each fuel model. For example, the estimated area to be represented by slash models 12 and 13 ranged from 5% to 30% of the total. The range of uncertainty is defined explicitly later in this section. Note that some of this uncertainty is due to the approximate nature of the stylized fuel models. A typical uncertainty was whether to represent an area with brush, some old slash, and partial timber as a model 12 type or a model 10 type. A working paper prepared in the early phases of this study discusses in more abstract terms some of the implications of using stylized fuel models and provides some insights on when it may be more appropriate to use direct assessment of fuel loading rather than stylized models.[6]

Fire Behavior.—For this analysis, fire behavior was represented by the fireline intensity (Byram 1959). Intensities used were calculated using the FIREBHV program described by Hirsch et al. (1981), which integrates historical fire records (Roussopoulos et al. 1980), fire weather station records (Furman and Brink 1975), and stylized fuel models (Albini 1976) with the Rothermel fire behavior model (Rothermel 1972) to generate cumulative probability distributions for fireline intensity. The uncertainty represented by the cumulative distribution reflects variation in weather. Probability distributions were produced for each fire weather station in or adjacent to the Clackamas and

[6] *Barrager, Stephen M., and David Cohan. 1979. Fuel information alternatives and fire behavior uncertainty. (Unplublished report on file at the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.)*

Estacada districts and for each stylized fuel model appropriate to the area. (A sample run is included in the appendix.) The distributions for the several fire weather stations were averaged to produce a single probability distribution for each stylized fuel model. Resulting probabilities for the three intensity classes recognized in this study are listed in the appendix.

An additional source of uncertainty is introduced by the necessarily approximate nature of the fire behavior model itself. The representation of this uncertainty is discussed later in this section.

Although we have attempted to separate the effects of fuel uncertainty from fire behavior uncertainty, it is important to note that the two are intimately related. Uncertainty in fuel conditions is one of several factors that contribute to fire behavior uncertainty. The distinction is made in this analysis to allow assessment of the relative importance of better fuel information in reducing the overall uncertainty regarding fire behavior.

Fire Size.—Even when one can assume that a particular fuel model is applicable and when weather conditions and fire behavior are known, there is still considerable uncertainty as to the final size of a fire. This is due to the actual spatial variations in fuel load and characteristics, topography, effectiveness of suppression activities, and other factors. Uncertainty in fire size given fire intensity and other factors was captured by probability encoding of expert opinion during a series of interviews and discussions with Mount Hood National Forest staff and will be discussed later.

Decision Tree Representation

Figure 6 shows a generalized decision tree representation of the fire management budget request decision and important uncertain factors. The box represents the decision, and the lines emanating from it represent decision alternatives. The circle nodes represent the uncertain variables. In this tree the decision and uncertainty, or chance, nodes are not connected. This convention is a shorthand representation of the tree where each node is connected to all branches of the preceding node.

The Cost-Plus-NVC Model

A simple quantitative model was developed to calculate fire management cost plus fire-induced, resource-value changes under various assumptions. The model is intended to provide a consistent framework for comparing alternatives and analyzing sensitivities. Its results should not be interpreted as precise predictions.

Overall Model Structure

The model is composed of a number of submodels, as shown in the block diagram of figure 7. The ignitions submodel divides ignitions into three classes by cause: industrial, other human-caused, and lightning. The nominal, or long-run, expected number of ignitions in each class is adjusted to reflect changes in prevention activities. In many of the model runs documented in the following section, the ignitions submodel was not used. The expected number of ignitions in each class, given prevention activities, was assessed and input directly into the fire location submodel. In a more detailed model, ignitions in each class might be expressed as a function of prevention or fuel treatment expenditures. The breakdown of annual ignitions used for most model runs (reflecting long-term averages based on Form 5100-29, Individual Fire Report data, adjusted for recent prevention activities) consisted of 1 industrial ignition, 25 other human-caused ignitions, and 8 ignitions caused by lightning.

The fuels submodel reflects the allocation of the total area (in this case, of the Clackamas and Estacada districts) to the appropriate stylized fuel models. This breakdown drives the fire location submodel. The nominal assignment of area to the fuel models was 280,000 acres to fuel model 10, 80,000 acres to model 8, and 20,000 acres each to the models 12 and 13. These values are the medians of the estimates provided by the Mount Hood National Forest staff.

The fire location submodel assigns ignitions to area types (each area type being represented by a stylized fuel model). All industrial ignitions are assumed to oc-

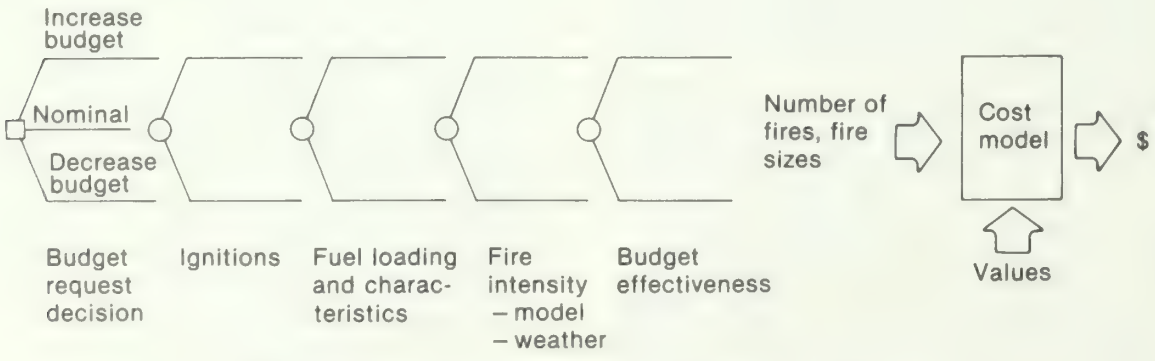


Figure 6.—Generalized decision tree for budget request decision.

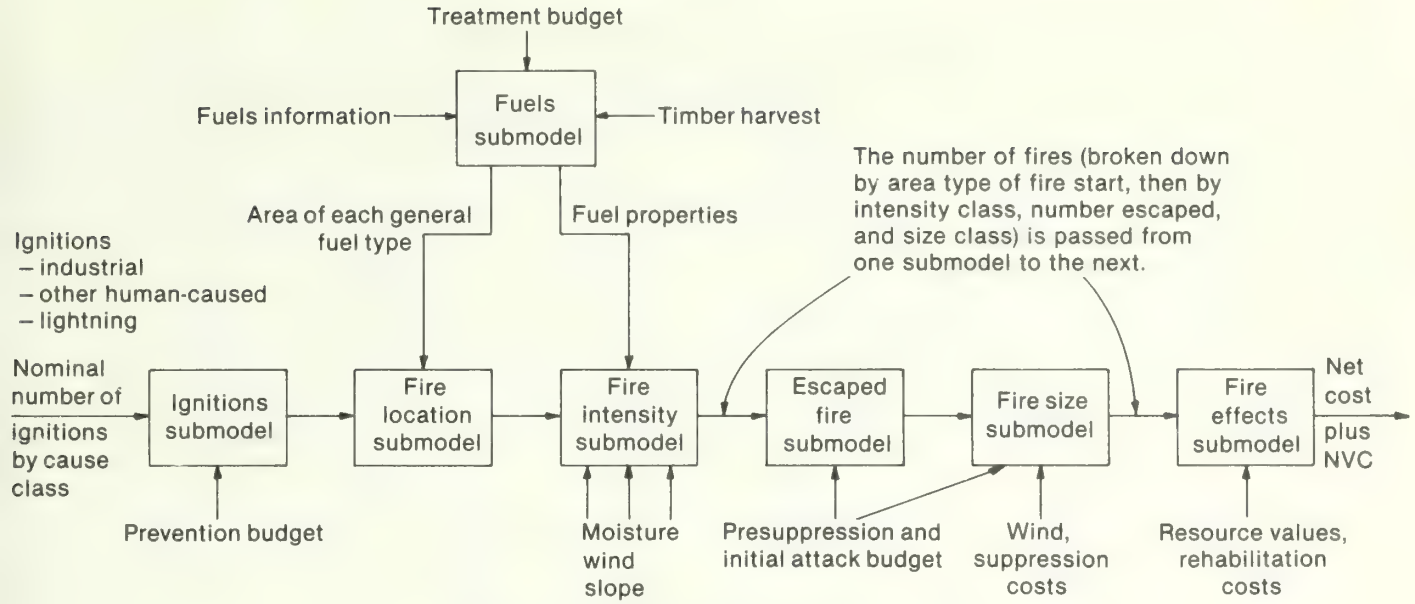

Treatment budget
Fuels information
Fuels submodel
Timber harvest
The number of fires (broken down by area type of fire start, then by intensity class, number escaped, and size class) is passed from one submodel to the next.
Area of each general fuel type
Fuel properties
Ignitions
– industrial
– other human-caused
– lightning
Nominal number of ignitions by cause class
Ignitions submodel
Fire location submodel
Fire intensity submodel
Escaped fire submodel
Fire size submodel
Fire effects submodel
Net cost plus NVC
Prevention budget
Moisture wind slope
Presuppression and initial attack budget
Wind, suppression costs
Resource values, rehabilitation costs

Figure 7.—Cost-plus-NVC model block diagram.

cur in slash areas. Other human-caused and lightning-caused ignitions are allocated to the area types in proportion to the number of acres assigned to each area type. It is possible that a greater proportion of lightning ignitions occur in model 8 areas, since such areas typically are at higher elevations. This would imply a shift of, perhaps, one or two ignitions per year from model 10 to model 8. Such a change would cause the model results to change by only a few percent. Using the nominal (base case) data for fire occurrence and fuel model area, the expected number of ignitions per year is about 23 in model 10 areas, 7 in model 8 areas, and 2 in each of the slash types (models 12 and 13).

The fire intensity submodel takes as input the number of fires in each area type and assigns the fires to intensity classes. Intensity classes used for most of the analyses were the following:

Intensity class	Btu·foot^{-1}·second^{-1}
Low	0–100
Medium	100–700
High	>700

An intensity of 100 Btu·foot^{-1}·second^{-1} is about the limit beyond which people are unable to work at the fire edge. At about 700 Btu·foot^{-1}·second^{-1}, spotting begins to be a problem and the limit of direct attack is reached. The basis for allocating the fires to intensity classes is a set of discrete approximations to the cumulative probability distributions generated by the FIREBHV computer program discussed previously. A discrete distribution is used for each area type (that is, for each stylized fuel model). For example, for the medium slash (model 12) stylized fuel model, there is a 3% chance of a low-intensity fire, a 61% probability of a moderate-intensity fire, and a 36% chance of a high-intensity fire. The complete distributions are listed in the appendix. Over all fuel types, one might expect about 25 fires per year in the lowest intensity class, about 6 in the intermediate class, and 3 in the highest intensity class.

The escaped fire submodel divides all fires (broken down by area type and intensity class) into those that are controlled by initial attack forces and those that escape initial attack. Escaped fires are defined to include those that are controlled by initial attack forces at a size exceeding that of the two lower size classes (nominally, greater than 20 acres) as well as those escaping initial attack efforts and requiring reinforcements. The fraction of fires escaping depends upon the area type (fuel conditions) and fire intensity class and is also affected by expenditures for presuppression activities and fuels treatment. The nominal escape fractions used in this analysis were based on the judgment of Mount Hood National Forest fuels and fire management staff, using the encoding method of Spetzler and Stael von Holstein (1975) and calibrated so that the model results reflect historical experience.

The fire size submodel divides the fires into the size classes of 0-1 acres, 1-20 acres, 20-200 acres, and greater than 200 acres. The fraction of fires assumed to be in each size class is a function of area type, intensity class, and whether or not the fires escaped initial attack. The fractions can be interpreted as a discrete probability distribution over fire size (conditional on intensity, stylized fuel model, and escape status). The distributions used were developed in cooperation with Mount Hood National Forest staff. The final distributions (listed in appendix) were developed through an interactive process of encoding experienced judgment and examining the quantitative implications (Spetzler and Stael von Holstein 1975).

The fire effects submodel assigns costs and resource value changes associated with fires. A table is entered giving the per-acre fire effects, such as changes in timber value and rehabilitation costs in thousands of dollars as a function of area type, intensity class, and size class. A typical cost was $1,000 per acre. The full table of costs is included in the appendix. For each fire category, the per-acre NVC is multiplied by the aver-

age size of fires in that size class. Total expected annual NVC is then calculated by multiplying these values by the number of fires in each category and summing over all size classes, intensity classes, and area types. Suppression costs are calculated in a similar manner. Nominal supression costs were assumed to be $500 per acre (except for the smallest size class). These values are then added to the fire management budget, resulting in the total annual cost plus NVC.

The general flow of the cost-plus-NVC model is to start out with the expected annual number of ignitions and break them down by location, intensity of the resulting fires, and fire size, as diagramed in figure 8. Since the effects of fires are generally not linear with size or intensity, the detailed breakdown allows fire damage costs to be assigned in a consistent manner.

The model equations can be summarized as follows:

$$IG(i) = \sum_{j} PR(i, j) \times IG(j)$$

where:

$IG(i)$ = the annual ignition rate in area type i (represented by fuel models 8, 10, 12, and 13),

$PR(i, j)$ = the fraction of ignitions from source j (industrial, other human-caused, or lightning) that occur in area type i,

$IG(j)$ = the annual number of ignitions from source j.

$$\text{Expected Total NVC} = \sum_{i} \sum_{k} \sum_{l} \sum_{m} IG(i) \times INT(i, k) \times ESC(i, k, l) \times SIZE(i, k, l, m) \times NVC(i, k, m)$$

where:

$INT(i, k)$ = probability of intensity class k given area type i,

$ESC(i, k, l)$ = probability of escape status l (yes or no) given area type i and intensity class k,

$SIZE(i, k, l, m)$ = probability of size class m given area type i, intensity k, and escape status l,

$NVC(i, k, m)$ = per acre net resource value change given area type i, intensity class k, and size class m.

$$\text{Expected Total Cost} + \text{NVC} = \text{Expected Total NVC} + \text{Budget Cost}$$

Base Case Data

Data were developed in cooperation with staff from the Mount Hood National Forest. Both historical records and judgment based on on-site experience were used. Data used for the cost-plus-NVC model base case are listed in the appendix.

Base Case Results

Base case results are listed in tables 2a and 2b. Table 2a gives a complete summary, while the detailed results broken down by the type of area in which a fire starts are listed in table 2b. The expected number, size distribution, and total burned area of fires calculated for the base case very closely reflect recent experience on the Clackamas and Estacada districts. The numbers are not meant to represent any particular year, but rather a long-term average. The results are based upon a fire management budget at roughly current levels, totaling about $743,000 for the Clackamas and Estacada districts, of which $477,000 is for fuel treatment.

Of the average of 34 annual ignitions, about 28 are expected to be controlled at a very small size. Fires reaching an average size of 10 acres occur at an average rate of roughly five per year. One might expect a fire in the 100-acre class once every one to two years and a very large fire (of approximately 1,000 acres) about once every 15 years. Note that these are to be interpreted as long-run averages. The occurrence of a large fire in any given year does not imply that several years must pass before another is possible.

Examination of the base case summary results leads to some interesting observations. Fires in the highest intensity class lead to over 60% of the net resource damages, although the expected number of such fires is only about three per year. It is reasonable that the most intense fires have the greatest chance of burning over a large area and of having the greatest effect on timber and other resources. Although only about 13% of the fires start in areas best represented by slash stylized fuel models, such fires account for over 47% of all fire damage costs. It follows directly that fires starting in slash have a greater chance of reaching higher intensities than do those starting in timbered areas. Fuel model 8 is almost "fireproof" under the weather conditions of the Mount Hood National Forest. All fires in areas represented by this model were in the lowest intensity class, resulting in insignificant resource value changes.

Sensitivity Analysis

Sensitivity analysis serves two purposes. Its primary intent is to identify which of the many uncertain parameters are critical to a given decision. This identification allows the uncertainty in the variables to which the decision is most sensitive to be represented explicitly by a probability distribution. Such a representation is prerequisite to any calculations of the economic value of improved information. The second purpose of sensitivity analysis is to provide insight into the behavior of the system. This was particularly useful in the analysis of the fire management budget-request decision.

Because we are not concerned with actually identifying the optimum budget level for the two districts, it is not necessary to specify fully the quantitative relationship between the budget level and expected NVC (i.e.,

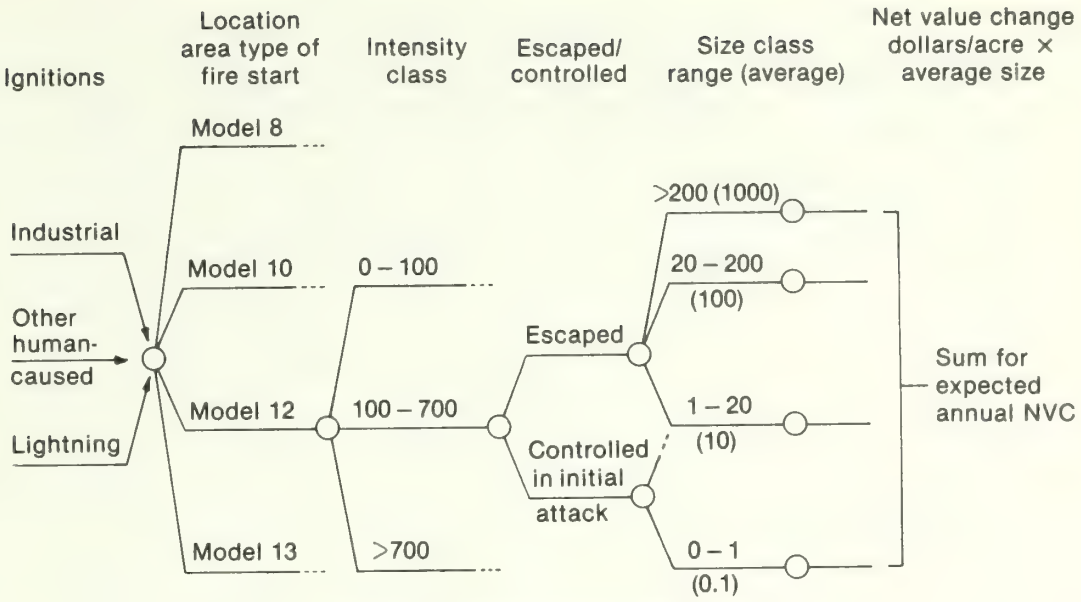


Figure 8.—Flow of cost-plus-NVC model.

Table 2a.—Base case results: Summary

Item	Area type at fire origin (fuel model)				
	Heavy slash (13)	Medium slash (12)	Timber litter (8)	Litter + understory (10)	Total
Average number of fires per year by size class:					
0.1 acres	0.54	0.97	6.27	19.92	27.70
10 acres	1.33	0.98	0.33	2.80	5.44
100 acres	0.26	0.19	0.00	0.35	0.79
1,000 acres	0.03	0.02	0.00	0.02	0.07
Total	2.15	2.15	6.60	23.10	34.00
Average number of fires per year by intensity class:					
Low	0.00	0.06	6.60	18.02	24.68
Moderate	0.60	1.31	0.00	4.39	6.30
High	1.55	0.77	0.00	0.69	3.01
Total	2.15	2.15	6.60	23.10	34.00
Expected NVC ($1,000/year) by intensity class:					
Low	0.00	0.01	0.79	2.14	2.94
Moderate	6.31	13.55	0.00	74.67	94.52
High	64.84	32.42	0.00	52.13	149.39
Total	71.15	45.98	0.79	128.94	246.85
Total suppression cost ($1,000/year)			= 100.4		
Budget (including fuel treatment, $1,000/year)			= 743.0		
Total cost + NVC ($1,000/year)			= 1090.0		

the budget effectiveness), as was done in studies by Schweitzer et al. (1982) and U.S. Department of Agriculture, Forest Service (1980a). Rather, we chose to analyze several parameters of the budget decision, exploring a range of assumptions about budget effectiveness. Formulating the problem in this manner, we did not use the standard practice of directly testing the sensitivity of the decision to uncertainty in important variables. Instead, the method used involved carrying out extensive tests of the sensitivity of the outcomes (primarily resource value changes and associated suppression costs) to variations in input values and

Table 2b.—Base case results: Details (by intensity and size class)

Intensity class	Size class: 0.1 average acres	10 average acres	100 average acres	1,000 average acres	Total
Area type: Heavy slash (model 13) Number of ignitions: 2.15					
			Number of fires (*average/year*)		
Low	0.00	0.00	0.00	0.00	0.00
Moderate	0.36	0.21	0.03	0.00	0.60
High	0.19	1.11	0.22	0.03	1.55
Total	0.54	1.33	0.25	0.03	2.15
			Net value change (*$1,000/year*)		
Low	0.00	0.00	0.00	0.00	0.00
Moderate	0.02	1.05	3.43	1.81	6.31
High	0.01	8.36	26.75	29.72	64.84
Total	0.03	9.41	30.18	31.53	71.15
Area type: Medium slash (model 12) Number of ignitions: 2.15					
			Number of fires (*average/year*)		
Low	0.06	0.00	0.00	0.00	0.06
Moderate	0.81	0.42	0.07	0.00	1.30
High	0.09	0.56	0.12	0.02	0.79
Total	0.96	0.98	0.19	0.02	2.15
			Net value change (*$1,000/year*)		
Low	0.00	0.00	0.00	0.00	0.01
Moderate	0.04	2.10	7.48	3.93	13.55
High	0.00	4.18	13.37	14.86	32.42
Total	0.05	6.28	20.85	18.80	45.98
Area type: Timber litter (model 8) Number of ignitions: 6.6					
			Number of fires (*average/year*)		
Low	6.27	0.33	0.00	0.00	6.60
Moderate	0.00	0.00	0.00	0.00	0.00
High	0.00	0.00	0.00	0.00	0.00
Total	6.27	0.33	0.00	0.00	6.60
			Net value change (*$1,000/year*)		
Low	0.13	0.66	0.00	0.00	0.79
Moderate	0.00	0.00	0.00	0.00	0.00
High	0.00	0.00	0.00	0.00	0.00
Total	0.13	0.66	0.00	0.00	0.79
Area type: Timber litter + understory (model 10) Number of ignitions: 23.1					
			Number of fires (*average/year*)		
Low	17.12	0.90	0.00	0.00	18.02
Moderate	2.72	1.40	0.25	0.01	4.39
High	0.08	0.50	0.10	0.01	0.69
Total	19.92	2.80	0.35	0.02	23.10
			Net value change (*$1,000/year*)		
Low	0.34	1.80	0.00	0.00	2.14
Moderate	0.27	21.07	37.53	15.80	74.67
High	0.01	9.98	19.96	22.18	52.13
Total	0.63	32.85	57.48	37.98	128.94

assumptions. The sensitivity information was then used as a basis for understanding, in a qualitative sense, the sensitivity of the budget decision to the inputs and assumptions.

A representative set of sensitivity tests is listed in table 3. Data used in the sensitivity tests are listed at the end of the appendix.

Critical Uncertainties

The sensitivity analysis showed that the fire loss estimates are quite sensitive to variations in the distribution of area (or fuel) types and to changes in fire intensity given the fuel type. As listed in table 3, doubling the assessed area represented by slash styl-

Table 3.—Sensitivity analysis (thousands of dollars per year)

Sensitivity case	Expected NVC	Expected suppression costs	NVC + suppression costs: differences from base case	
Base case	247	100	---	
Ignitions				
Subtract one industrial ignition	220	88	−39	(−11%)
Subtract one other human-caused ignition	240	98	−9	(−3%)
Slash area				
50% less slash area	202	80	−65	(−19%)
100% more slash area	369	164	+186	(+54%)
Fire intensity				
2 × fire intensities	560	191	+404	(+116%)
1/2 × fire intensities	200	84	−63	(−18%)
Number of escaped fires				
10% more escaped fires	268	109	+30	(+9%)
25% more escaped fires	301	121	+75	(+22%)
10% fewer escaped fires	225	92	−30	(−9%)
25% fewer escaped fires	193	80	−74	(−21%)
Values				
2 × NVC figures	494	100	+247	(+71%)
1/2 × NVC figures	123	100	−124	(−36%)

ized fuel models results in a 54% increase in the expected losses. This change occurs even though only 10% of the total area has been changed from the nonslash to the slash fuel types. Similarly, doubling the fire intensities more than doubles expected fire losses. A greater percentage of areas with high fuel loadings will lead to more fires having higher intensities. As was noted in the discussion of the base case results, these are the fires that produce the greatest resource impacts. An analogous effect is clear if all fires have higher intensities.

The great sensitivity of the outcomes to changes in the distribution of area types and fire intensities suggests that the budget decisions will also be sensitive to such uncertainties. For example, if one assumes that greater budget expenditure results in improved control effectiveness, such an increased budget is preferable given a greater percentage of area with high fuel loadings. On the other hand, lower fire intensities, less area with high fuel loadings, or a combination of the two may allow one to reduce the budget and realize a net reduction in cost plus NVC. (The fire intensity and area distribution uncertainties are modeled explicitly in the subsection Value of Information Analysis. The economic value of obtaining more information to reduce the uncertainties is discussed at that point.)

The outcomes of the annual budget request decisions are also sensitive to the annual number of ignitions. The optimal alternative varies symmetrically with the number of ignitions: More ignitions suggest a higher budget, and vice versa. This sensitivity was not as great as that found for area distribution and intensity, and few information-gathering options are available to reduce uncertainty in the number of future ignitions. This does not imply that expenditures on prevention activities will not reduce the number of ignitions; that is an action that changes the system rather than an information gathering activity. Thus it was deemed appropriate to evaluate the budget decision and value of information on the basis of the expected annual number of ignitions.

Although many fire management decisions are highly sensitive to daily fluctuations in weather, the budget-level decision is necessarily based on long-term climatological patterns. These patterns are generally well represented in the historical record. As a result, the decision is relatively insensitive to the low degree of uncertainty in the local long-term weather distribution. Spatial weather variations are important for detailed pre-attack planning, but they do not appear to significantly affect the overall annual budget decision when fire weather stations are properly located.

The effectiveness of various fire management and fuels treatment expenditures—that is, the effectiveness of the fire budget—is of considerable importance. It is also poorly understood. In formal terms, there is a wide range of uncertainty in the effectiveness of control resulting from a given budget level. In the present analysis, this uncertainty was investigated in two ways: The value of information on other parameters was calculated for a range of assumptions regarding budget effectiveness, and a simplified value of information calculation was carried out for the uncertainty in effectiveness itself.

The changes in resource value that result from fires of various intensities and sizes are subject to much debate. While timber values are reasonably well-known, the change in such values caused by fires (of varying intensity and extent) is uncertain. Other resource values, such as watershed or wildlife, rarely have explicit quantitative value assignments. Rather than interpreting this as an uncertainty that might be reduced with further information, we chose to evaluate the decision and the value of information over a wide range of possible fire damage costs or losses. The sensitivity of such values to variations in the losses is then evident.

We have not included an explicit test of sensitivity to the fire size distributions (i.e., to the distribution of fire sizes given area type, intensity, and escape status). The outcomes will clearly be sensitive to the probabilities of large fires. The distributions used (as listed in the appendix) reflect the best judgment of several Mount Hood National Forest fuels and fire managers and are also consistent with historical data. We have chosen to hold these distributions fixed, as a modeling assumption, to reduce the degrees of freedom in the model.

Insights from Sensitivity Analysis

The importance of sensitivity analysis goes beyond its role in identifying critical uncertainties. It can provide insights to help in understanding the system itself as well as decisions concerning its management.

Because of the uncertainty in budget effectiveness, it is not possible to provide a detailed analysis of the allocation of the overall fire management budget to particular budget categories. The sensitivity analyses do give, however, some feel for this issue. For example, the annual expected values of eliminating one industrial ignition or one other-human-caused ignition are, respectively, about $39,000 and $9,000. The costs of having an additional ignition in either category are similar. These values compare to a current prevention budget of about $58,000 for the Clackamas and Estacada districts. If the prevention budget effectiveness is such that the number of nonindustrial ignitions can be expected to be reduced by one for an additional expenditure of less than $9,000, such a budget allocation is worth considering. On the other hand, if reducing the prevention budget by an amount greater than $9,000 led to an increase in the expected number of ignitions by less than one, then such an alternative should be pursued.

The effectiveness of fuel treatment activities in reducing wildfire losses is subject to much controversy. While the scope of analysis precludes detailed investigation of this issue, the sensitivity analysis may provide some insight. If the amount of area having a fuel load best represented by the slash stylized fuel models could be reduced by 50%, the action would have an expected annual benefit on the order of $65,000. Recall that this is for the Clackamas and Estacada districts only. The value would be greater for the entire Mount Hood National Forest. Furthermore, it involves only fire-related savings. Direct benefits of slash treatment to resource values (e.g., enhanced esthetic values, better regeneration success, etc.) are not included.

This expected savings would accrue over each year that the slash area was maintained at a level of 50% below the present level. Comparing the costs of such treatment activities with this value will give some feel as to whether the present fuels treatment budget of $477,000 is appropriate as a fire management expenditure.

Holding all other factors constant (in particular, area distribution and fire intensities), the value of reducing the number of escaped fires by 10% is about $30,000 per year. The added cost of allowing 10% more fires to escape initial attack is similar. If increasing the presuppresion budget by an amount less than $30,000 can achieve a 10% reduction in escapes, such a budget increase would be desirable. Conversely, if more than $30,000 can be saved from the budget by allowing 10% more fires to escape, this alternative should be seriously considered.

Value of Information Analysis

Three different value-of-information analyses were carried out for the fire management budget request decision. The value of reducing uncertainty in the assignment of forest area to the available stylized fuel models and in predicting fire intensity given fuel type was investigated in some detail. Brief discussions of the value of information on budget effectiveness and the value of adding an additional stylized fuel model to the available set follow.

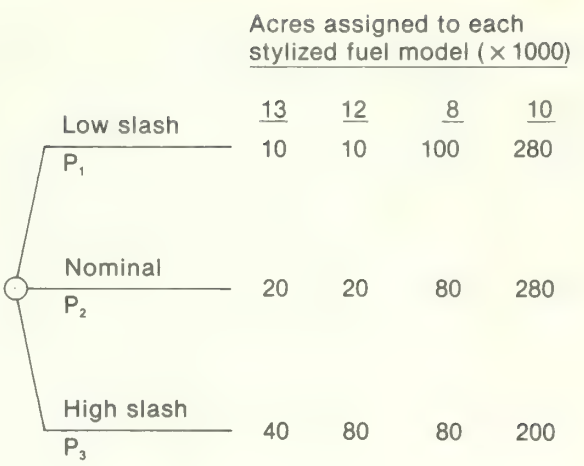
Value of Information: Fuels and Fire Intensity

Before examining the value of information in detail, it is necessary to define more fully the decision being analyzed. In general terms, the alternatives are to request an increase in the fire management budget, to request the present budget level, or to request a lower budget. Several different amounts of potential budget increase or decrease were investigated. The uncertainties considered explicitly are the assignment of stylized fuel models to the total area (area distribution) and the fire intensity given fuel type and weather characteristics (intensity). The outcomes are expected values for total budget, net resource value changes, and suppression costs. The decision criterion is to minimize expected costs plus NVC. Other than for budget alternatives, area distribution, and fire intensity, all data used reflect the base case discussed earlier in this section. (Data for the base case are summarized in the appendix.)

To provide an internally consistent framework for evaluation, a parametric approach was used to model the change in fire control effectiveness given changes in budget. It was assumed that changes in fire management budget change the probability of controlling a fire with intial attack forces. This could occur through changes in presuppression, fuels treatment, or initial attack activities. Changing the probability of achieving control during initial attack implies a change in the number of escaped fires—the dominant category in fire losses. Two cases were examined, one in which increasing or decreasing the fire budget by some arbitrary amount causes a 10% increase or decrease in the number of escaped fires and one in which a budget change results in a 50% increase or decrease in escapes. The magnitude of budget change needed for these effectiveness changes was varied, providing a range for the value of information calculations.

Note that we are examining decisions involving incremental changes in the budget level. Similar incremental decisions at different base budget levels will result in different information values, but likely on the same order of magnitude as those found in this case study.

Area Distribution Uncertainty.—Uncertainty in the assignment of stylized fuel models to the Clackamas and Estacada districts is represented in figure 9. The range of possible assignments was approximated by a discrete probability distribution over the three breakdowns: a nominal (or most likely) distribution, a low-slash case, and a high-slash case. Five fire management specialists from the Mount Hood National Forest participated in the encoding session at which this distribution was defined. Figure 9 represents their consensus view. The probabilities used (0.3, 0.4, 0.3) reflect a discrete approximation of the continuous distribution implied by the consensus that the probability is low that the amount of slash will exceed the high-slash case or fall below the low-slash case. The reduced uncertainty case can be given two alternative interpretations: (1) For a national forest such as the Mount Hood, it represents the uncertainty remaining after more (but still imperfect) information is made available, or (2) it represents the initial uncertainty for a forest having better information on fuel conditions at the outset.

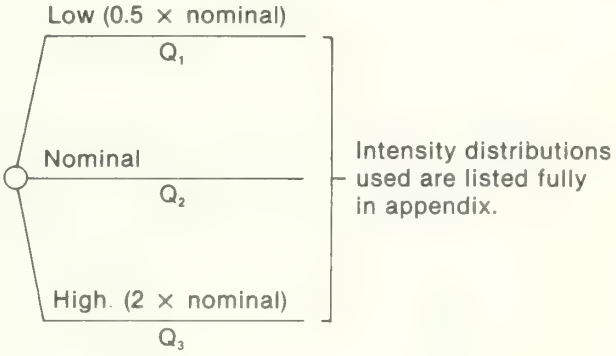


Probability distributions	P_1	P_2	P_3
Nominal uncertainty	0.3	0.4	0.3
Reduced uncertainty	0.1	0.8	0.1

Figure 9.—Area distribution uncertainty.

Fire Intensity Uncertainty.—The uncertainty in fire intensity, given an accurate choice of fuel models, is represented in figure 10. As noted previously, the nominal intensities are those calculated directly by the Rothermel (1972) fire behavior model. Actual fireline intensities can be expected to fall within the range of one-half of the nominal model-generated fire intensity up to twice the nominal intensity output (Albini 1976). This uncertainty in fireline intensity is approximated by the nominal probability distribution listed in figure 10 for the half-nominal, nominal, and two-times-nominal intensities.

Each of the three cases forming the branches of the probability node in figure 10 is actually a set of four distributions (with weather variations factored in) on fireline intensity—one for each fuel model. The discrete versions of these distributions are shown in the appendix. The nominal case is included with the base case data, and the half- and double-intensity cases are found with the sensitivity analysis data.



Probability distributions	Q_1	Q_2	Q_3
Nominal uncertainty	0.3	0.4	0.3
Reduced uncertainty	0.1	0.8	0.1

Figure 10.—Fire intensity uncertainty.

Decision Tree.—The complete decision tree used for the analysis of the value of information on area distribution among fuel models and on fire intensity is shown in figure 11. Outcome values (total cost plus NVC—excluding fuel treatment and brush disposal costs) are listed for two decision situations, for which the alternatives of raising or lowering the fire budget result in either a 10% change or a 50% change in the number of fires escaping initial attack. The budget increments necessary to produce these changes in effectiveness—that is, the budget changes implied by the increase or decrease alternatives—are denoted as Δ_1 and Δ_2. The uncertainties in the distribution of fuel model types and in fire intensities are shown explicitly. Probabilities for the area distribution uncertainty are shown in figure 9. Probabilities describing the uncertainty in intensity are listed in figure 10.

Analysis.—Cases representing a wide range of situations were evaluated. The optimal decision alternative and expected cost plus NVC given the initial uncertainty, the value of perfect information on the area distribution, and the value of perfect information on fire intensity were determined for each case. The deci-

sion tree shown in figure 11 provided the framework for these computations. Varied over the cases are the effect of the budget increase or decrease alternatives (+/−10% or +/−50%), the cost of effecting these changes (Δ_1 and Δ_2), and the initial uncertainty in area distribution and fire intensity (see figures 9 and 10). A summary of some of the most interesting cases is provided in table 4. A complete list of cases can be found in table 5. Information values are given in dollars per acre per year.

For decisions involving relatively small changes in the budget level (on the order of 10-20%), the value of obtaining perfect information on the distribution of fuel types was very small, typically less than one cent per acre per year (e.g., scenarios 1 through 5 in table 4). Most annual decisions regarding budget level will involve alternatives of this magnitude, which corresponds to an information value of roughly $10,000 per year for the Mount Hood National Forest. Recall that this is the value of perfect information. Most information-gathering alternatives will still leave one short of certainty. For the decisions involving incremental changes in budget, the value of perfect information on fire intensity was generally in the range of one to three cents per acre per year, which corresponds to $10,000 to $30,000 per year for the Mount Hood National Forest. Representative cases are found in table 4.

When decisions involving greater changes in resource allocations are considered, it is reasonable to expect that the value of reducing uncertainty will be greater. The analysis results confirm this supposition. When a major decision is contemplated, such as raising or lowering the budget by about 50% of the present level, the value of reducing uncertainty increased significantly. The expected value of perfect information on the distribution of area types, in the context of such major decisions, ranged from zero to seven cents per acre per year. The value of fire intensity information, on the other hand, was as high as 19 cents per acre per year. Most values were less than 10 cents per acre per year (see scenarios 6 and 7 in table 4). For the Mount Hood National Forest, one cent per acre corresponds roughly to $10,000.

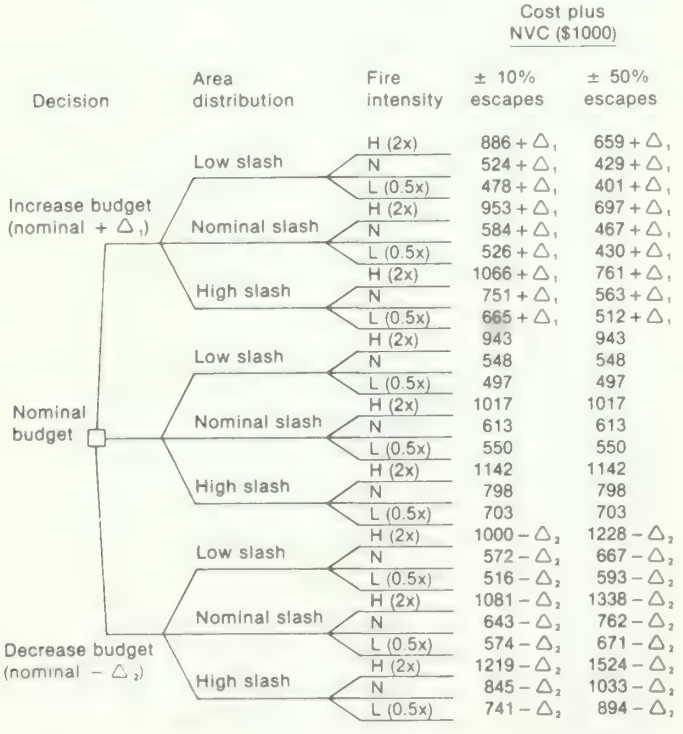


Figure 11.—Budget analysis decision tree.

Some general patterns are apparent in the range of situations analyzed. The value of reducing uncertainty about fire intensity, given a proper fuel model, was virtually always greater than that for reducing uncertainty in the area distribution of fuel models. Many situations in which more information on the distribution of fuels would not change the budget decision—and, thus, would have no economic value—still showed a positive EVPI for fire intensity.

For either uncertain parameter, changing the initial probability distribution from the nominal to the reduced uncertainty case resulted in a reduction in the EVPI of 50-75%. One might conclude that the value of new information that would allow this degree of reduction in uncertainty is about one-half of the nominal EVPI. This implies that the value of such imperfect information on the distribution of fuel types for the Mount Hood National Forest is no more that $5,000 per year in the context of annual incremental budget decisions. The value of improved but imperfect information on fire intensity would be about $10,000 annually. These values would be about three times larger if decisions regarding major portions of the budget (e.g., 50%) were faced.

An interesting pattern found for decisions involving relatively small fractions of the existing budget was that reducing the initial uncertainty in fire intensity often induced an increase in the EVPI on the fuel model area distribution. This suggests that a synergism may exist. Investing resources in developing an improved fire behavior model (and thus reducing uncertainty in intensity given the fuel distribution) can actually increase the value of gathering more information on fuel properties and distributions. Results of ongoing research to improve fire behavior prediction capabilities may eventually justify expenditures larger than one or two cents per acre per year for better fuel information.

Situations in which the effectiveness/budget relationship was assumed to be linear about the nominal budget level (equivalently, constant returns to scale) generally had lower information values than were found for cases in which the budget increase required for improved effectiveness was significantly different from that saved in return for accepting less effectiveness. For example, scenario 1 in table 4 is a case in which a 10% increase or decrease in budget results in the same (+/−10%) change in effectiveness (the number of escaped fires). This decision scenario has zero EVPI values for information on both fuel distribu-

Table 4.—Value of information cases: Summary

Decision scenario	Best alternative under uncertainty	Expected cost + NVC	Expected value of perfect information: On area distribution	Expected value of perfect information: On fire intensity
		$1,000/year	*dollars per acre per year*	
1. Alternatives include nominal and +/−10% of presuppression, prevention and initial attack budget to produce +/−10% in escapes	Increase budget	729	0.00	0.00
2. Same as 1, except with reduced initial uncertainty on intensity	Increase budget	671	0.00	0.00
3. Alternatives include +/−15% of budget to produce +/−10% escapes	Increase budget	742	0.01	0.03
4. Same as 3, except with reduced initial uncertainty on both area and intensity	Decrease budget	652	0.005	0.01
5. Alternatives include +10%/−20% of budget to produce +/−10% escapes	Increase budget	729	0.01	0.03
6. Alternatives include +/−60% of budget to produce +/−50% in escapes	Increase budget	698	0.00	0.04
7. Alternatives include +75%/−50% of budget to produce +/−50% escapes	Increase budget	738	0.04	0.08

Table 5.—Value of information results

Δ_1	Δ_2	Area distribution uncertainty[1]	Fire intensity uncertainty[1]	Best alternative under uncertainty[1]	Expected value	EVPI: On fuel load and location	EVPI: On fire intensity
percent of budget					*$1,000/year*	*dollars per acre per year*	
			Scenarios involving +/−10% of escaped fires				
10	[2]10	N	N	+	729	0.00	0.00
10	[3]10	N	R	+	671	0.00	0.00
10	10	R	N	+	712	0.00	0.003
10	10	R	R	+	652	0.00	0.001
15	[4]15	N	N	+	742	0.01	0.03
15	[5]15	R	R	−	652	0.005	0.01
10	15	N	N	+	729	0.001	0.01
15	10	N	N	+	742	0.008	0.02
10	[6]20	N	N	+	729	0.01	0.03
20	10	N	N	N	737	0.00	0.009
5	10	N	N	+	716	0.00	0.00
10	5	N	N	+	729	0.00	0.00
			Scenarios involving +/−50% of escaped fires				
50	50	N	N	+	672	0.00	0.00
60	[7]60	N	N	+	698	0.00	0.04
40	40	N	N	+	645	0.00	0.00
75	75	N	N	+	738	0.07	0.17
75	75	N	R	−	660	0.02	0.06
75	75	R	N	−	722	0.03	0.19
75	75	R	R	−	627	0.02	0.06
60	30	N	N	+	698	0.00	0.02
30	60	N	N	+	618	0.00	0.00
75	[8]50	N	N	+	738	0.04	0.08
75	50	N	R	N	679	0.03	0.03
50	75	N	N	+	672	0.007	0.05
50	25	N	N	+	672	0.00	0.00
25	50	N	N	+	605	0.00	0.00

[1] *N = Nominal; R = Reduced; + = Increase; − = Decrease*

[2] *Scenario 1 in table 4.*

[3] *Scenario 2 in table 4.*

[4] *Scenario 3 in table 4.*

[5] *Scenario 4 in table 4.*

[6] *Scenario 5 in table 4.*

[7] *Scenario 6 in table 4.*

[8] *Scenario 7 in table 4.*

tion and on fire intensity. In contrast, in scenario 5, the budget could be cut by 20% at the cost of accepting 10% more escapes, while decreasing the number of escapes by 10% requires only a 10% increase in the budget. This case has considerably greater EVPI results: \$0.01/acre/year for fuels information and \$0.03/acre/year for fire intensity information. This general pattern is reasonable: The nonlinear scenarios imply greater sensitivity to surprises or unlikely outcomes. Thus, the value of eliminating uncertainty in such cases is likely to be greater.

Value of Adding a Fuel Model

Part of the uncertainty in the assignment of acreage within the Clackamas and Estacada districts to stylized fuel model types can be attributed to the small number of fuel models from which one must choose. It is reasonable to wonder whether a finer grained set of fuel models would eliminate or reduce uncertainty.

A decision problem was set up in which it was assumed as an extreme case that all uncertainty in the area distribution was caused by an insufficiently detailed set of stylized fuel models and that all such uncertainty could be removed by the addition of one more model. This structure should provide an upper bound on the value of adding another fuel model to the existing set in the context of fire management budget decisions.

Forest personnel seemed to have greatest difficulty assigning an appropriate fuel model to areas where slash had been overgrown by brush. A new fuel model was constructed to specifically represent this situation. Its fire behavior characteristics were intermediate to those of models 12 and 13.

The upper decision tree in figure 12 describes the decision situation when only the existing set of fuel models is available. The uncertainty as to how the area should be assigned to the available stylized models is shown explicitly. The lower tree in the figure represents the situation when the new stylized model is available; no uncertainty remains (again, note that this is purposely an extreme case). The decision alternatives are again whether to increase the fire management budget, leave it at the current level, or decrease the budget. The effectiveness of increasing or decreasing the budget was modeled by a 10% increase or decrease in the number of escaped fires. The uncertainty in budget effectiveness was explored by varying Δ_1 and Δ_2 over a wide range to ascertain the sensitivity to these parameters.

The results of this analysis were rather clear: Creating an additional stylized fuel model (and thus removing a source of uncertainty) generally did not result in a change in the preferred alternative. In such cases, since the additional model failed to change the decision, its availability had no value. Only a few instances (settings of Δ_1 and Δ_2) were found in which a different alternative was shown to be optimal when the fifth fuel model was added. Such cases, however, were those in which the alternatives resulted in outcomes

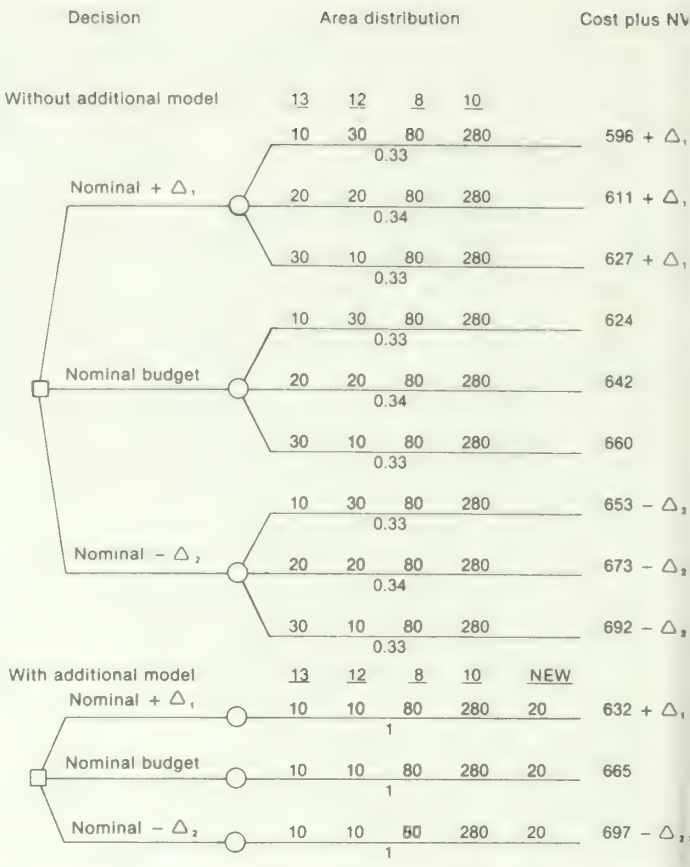


Figure 12.—Decision trees without and with an additional stylized fuel model.

that were so close that the cost of a "wrong" decision was insignificant. For example, in a case where both Δ_1 and Δ_2 were assumed to be \$32,000 (about 12% of the nominal budget), the decision when limited to four stylized models was to maintain the nominal budget level. When the new fuel model was added, the budget increase alternative was preferred. By examining the alternative from the first four-model case (nominal budget) in the five-model decision structure, we find an increase in cost plus NVC of only \$1,000, or approximately one-tenth of 1%. These results are insensitive to variations of 50-200% in the area allocated to the hypothetical new stylized fuel model.

We would conclude that for the purposes of the budget-level decision in areas such as the Mount Hood National Forest, the existing set of 13 stylized fuel models (Albini 1976) provides sufficient resolution. A more detailed set of models may be of value for other decision contexts.

Value of Information: Budget Effectiveness

It has been noted several times that the effectiveness of the fire management budget is uncertain. It is not well understood how great a change in effectiveness (and, ultimately, fire costs and resource value changes) will result from a given change in the fire management budget. In the analyses presented earlier, the implications of this uncertainty were examined by calculating information values for a range of effectiveness

change/budget change scenarios. At this point, we will examine the uncertainty explicitly with a simplified decision problem.

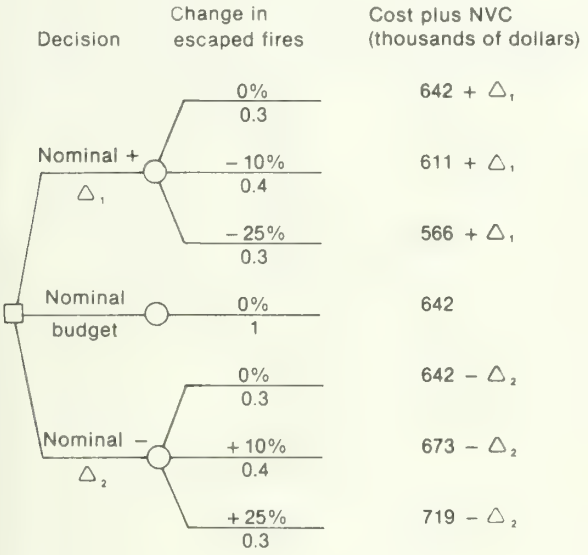
The decision tree for this analysis is shown in figure 13. Uncertainty in area distribution and fire intensity is suppressed. It was assumed that it was uncertain what change in the number of escaped fires would result from a given change in budget. The three points modeled in the tree are no change, 10% change, and 25% change. Again, several budget change levels were examined to produce a range for the expected value of perfect information. Typical values were about five cents per acre per year, or about $50,000 annually for the Mount Hood National Forest. It should be reiterated that this is the value of perfect information and thus an upper bound on the cost of any information-gathering efforts to resolve uncertainty in the relationship between the presuppression budget and initial attack effectiveness.

Information Alternatives

Fuel Loading/Distribution of Fuel Types

The EVPI on the distribution of area types was on the order of $10,000 per year for the Mount Hood National Forest. This is clearly not enough to support any significant ground-level, information-gathering activity, although future changes in ignition risk, resource values, and levels of other uncertainties could someday make these intensive activities worthwhile. For now, expenditures only up to one or two cents per acre per year on efforts to improve the classification of the forest by fuel model may be justified. Periodic examination by air of slash/brush conditions in old cut-blocks or use of an improved system of record-keeping to better utilize information already available (e.g., from timber cruises, timber sale records, fuels treatment activities, and other resource management functions) could probably be accomplished at this cost. Note that for fire management budget analysis purposes, the spatial pattern of fuel types is less important than the aggregate amount of area best represented by each type. The fire budget decision is sensitive to the overall fire hazard level but not to the detailed pattern of fire activity.

Funds invested in developing systems applicable to many national forests may be of greater value. For example, $3,000 per year per forest multiplied by 70 forests implies a research budget for aggregate fuels inventory systems of roughly one-quarter of a million dollars per year. Such a value would be appropriate only if results found for other national forests are of the same order of magnitude as those found in this case study.



Budget change (percent of nominal)		EVPI (dollar • acre $^{-1}$ • year $^{-1}$)
Δ_1	Δ_2	
10%	10%	$0.04
15%	15%	0.05
20%	20%	0.04
10%	15%	0.06

Figure 13.—Decision tree for evaluating EVPI on budget effectiveness.

Fire Behavior/Fire Intensity

Information useful in refining estimates of fire behavior would generally take two forms: improved understanding of the physical processes involved and improved models to explicitly represent these processes. Research in these areas would presumably be applicable over broad regions or over the entire country, as opposed to a single forest. This suggests that the cost of such research should be compared to the aggregate value of information over the country or the region involved.

The expected value of perfect information on fire behavior (specifically fireline intensity), given fuel load and weather conditions, was found for the Mount Hood National Forest to be on the order of $20,000 annually (assuming that the majority of budget decisions are of the incremental nature, as opposed to a major (i.e., +/−50%) change). It is likely the research leading to improved models and experimental calibration of such models would reduce uncertainty but not eliminate it. Comparison of the EVPI for the reduced uncertainty case with that for the nominal case suggests that the annual value to the Mount Hood National Forest of such an improved capability would be in the range of $5,000 to $10,000 per year. Aggregating over a specific region or over the entire National Forest System would give an idea of the potential value of such research for the purpose of fire management budget formulation.

Fire Management Effectiveness

The uncertainty in the relationship between budget level and the effectiveness of initial attack is of a different nature from those uncertainties discussed previously and has to do as much with the performance of personnel as with physical processes. Reducing such

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uncertainty would facilitate better decisionmaking regarding fire management expenditures. The upper bound on the value of such information for the Mount Hood National Forest is roughly $50,000 per year. Again, this is the expected value of perfect information. The resources that should be devoted to developing an improved understanding of budget effectiveness are likely to be considerably lower than $50,000 but can be significant when aggregated for the Forest Service as a whole.

FUEL TREATMENT DECISION

This section is a discussion of a site-specific decision: Which fuel treatment alternative is appropriate after a timber harvest operation? The structure and detail of the problem being analyzed are based on a specific harvest site on the Mount Hood National Forest. In addition, variations from the specific situation are examined to offer insight on a wider range of decisions of the same general type.

The Decision

The decision addressed in this section involves the choice of postharvest fuel treatment for a proposed 25-acre harvest. The site chosen for this analysis has characteristics that make the decision relatively complex (these characteristics are discussed later). Many fuel treatment decisions are much simpler in nature.

The Specific Site

The site under consideration consists of 25 acres of old-growth Douglas-fir with scattered white pine (*Pinus monticola* Dougl.) and hemlock (*Tsuga heterophylla* (Raf.) Sarg.) on the Clackamas District of the Mount Hood National Forest. Some understory growth is present, together with a significant quantity of timber litter. Preharvest loadings of fine woody fuels (less than 3 inches in diameter) are estimated to be on the order of 1-2 tons per acre. The area is at an elevation of 3,000 feet, with a southwest aspect. The slope is about 45%.

The proposed harvest area is to be clearcut, using a one-end suspended skyline system. All Douglas-fir and hemlock are to be cut; the white pine will be left as seed trees. An important characteristic of the site is its remoteness: Access is very poor.

In making the treatment decision, the fuel management staff faces several considerations:

1. A considerable, though uncertain, quantity of activity fuel (cutting slash) will be created during the harvest.
2. It is desirable to reduce the quantity of this fuel to create planting sites, reduce fire hazard, and improve wildlife habitat.
3. The poor access to the area makes treatment activities relatively expensive.
4. It is important to retain the duff/humus layer in order to protect site quality.
5. Damage to or destruction of a significant portion of the white pine stand will make hand planting necessary and greatly increase regeneration costs.

Alternatives Considered

Three alternatives under consideration by Mount Hood National Forest staff were evaluated, and further implications of some alternatives were investigated.

1. No Treatment.—The no-treatment alternative actually involves a very minimal treatment with spot treatment efforts by hand. The white pine would be retained, but planting sites would be of questionable quality, given the heavy load of activity fuels. The posttreatment fire hazard would be high. An important question involves the cumulative effects of selection of this alternative for a large number of sites. If the no-treatment alternative was selected for the majority of harvest sites, the amount of area in slash would increase. This would have implications on the overall level of fire hazard. The cost of the no-treatment alternative is very low—about $100 per acre.
2. Prescribed Burn.—The burn alternative involves a coarse (8 × 10) yarding of unmerchantable material (YUM) (removing all woody material greater than 8 inches in diameter and 10 feet in length) followed by broadcast burning. It has the advantage of providing a considerable reduction in fuel load at an intermediate cost. This must be balanced with the uncertainty in the outcome of the burn. A low-intensity burn may result in insufficient fuel reduction; or if the burn becomes too intense, it may result in damage to the white pine or the duff/humus layer. There is also the possibility of the fire's escaping prescription, with attendant costs and damages. The remote location of the site under consideration gives this alternative an estimated cost of $800 per acre.
3. Intensive.—The intensive treatment option involves YUM to a 6 × 6 standard. It has the advantage of greatly reducing risk to the white pine stands while providing significant reduction in fuel load. The cost is high—approximately $1,300 per acre. Because of the uncertainty in fuel load and site conditions, it is not possible to predict precisely the cost of achieving a given level of fuel load after treatment. This uncertainty can be modeled in a number of ways. We have chosen to represent it by assuming that the treatment cost is fixed, but that the amount of posttreatment fuel loading is uncertain and determined by the pretreatment load.

Decision Structure and Data

A sequence of decisions is involved in determining the form of fuel treatment for a specific site. These decisions range from the initial decision regarding the harvest to the final choices made by the crew carrying

out the prescribed treatment. Important uncertainties include the amount of preharvest (natural) fuels, the quantity of activity fuels created during the harvest, and the effects of the chosen treatment alternative. Timber values are reasonably well known, but the relationships among silvicultural technique, treatment method, and future timber production are complex and uncertain. Values related to other resource uses, such as watershed and wildlife, are poorly defined. In the analysis discussed later in this section, a wide range of sensitivity analyses and various decision scenarios were used to investigate the implications of different value assumptions and to provide insights into treatment decisions other than the specific case on the Mount Hood National Forest.

The complexity of the situation is illustrated in figure 14. Our discussion will emphasize the fuel treatment decision, and the analysis will focus principally on the postharvest treatment decision. In practice, the fuels management staff devotes considerable effort to the analysis of treatment alternatives before the harvest is carried out. The tentative choice of treatment is used to calibrate treatment costs during bidding for the harvest site by timber industry groups. The costs of a "wrong" decision (e.g., one that is changed after more information is available after the harvest) are due to the procedural details of the Forest Service/timber industry relationship. It is difficult to collect funds in excess of those originally estimated to be necessary, and there are incentives against refunds as well. Although the decision was complex, it was decided that the appropriate focus of this analysis was on the post- rather than the pre-harvest treatment decision. This way emphasis can be placed on the physical processes and systems rather than organizational and financial procedures and regulations.

The decision tree in figure 15 shows the postharvest treatment decision in greater detail. Implementing an analysis based on the structure of this decision required addressing several modeling and assessment issues.

Fuel Loading Uncertainty.—A critical uncertainty, both in analyzing the decision and determining the value of information, was in the quantity of fine fuels after harvest operations. Postharvest fine fuels (less than 3 inches) include both natural and activity fuels. The initial uncertainty in fuel load was assessed as follows. A Clackamas District fuels management specialist familiar with the site was shown a photo series representation of medium slash (Maxwell and Ward 1976) produced on a site similar to the one in question using a similar harvest technique. He was not allowed access to the published loading measurements accompanying the photograph. The visual information provided by the photo series was assumed to be representative of that provided by a postharvest inspection of the site. Standard interview techniques (Spetzler and Stael von Holstein 1975, Stael von Holstein 1970) were used to encode the subject's uncertainty about the actual quantity of fine fuels given that the chosen photograph accurately portrays on-site conditions. The resulting cumulative probability distribution is shown in figure 16.

The assessed distribution was approximated by a three-branch, discrete probability distribution (fig. 17), with probabilities of 0.25, 0.5, and 0.25, respectively, that the fuel loading is 8-14, 14-20, and over 20 tons per acre. This distribution was used in all subsequent analyses of the fuel treatment decision and provides the basis for calculation of the economic value of gathering more information on fuel load prior to making the postharvest treatment decision.

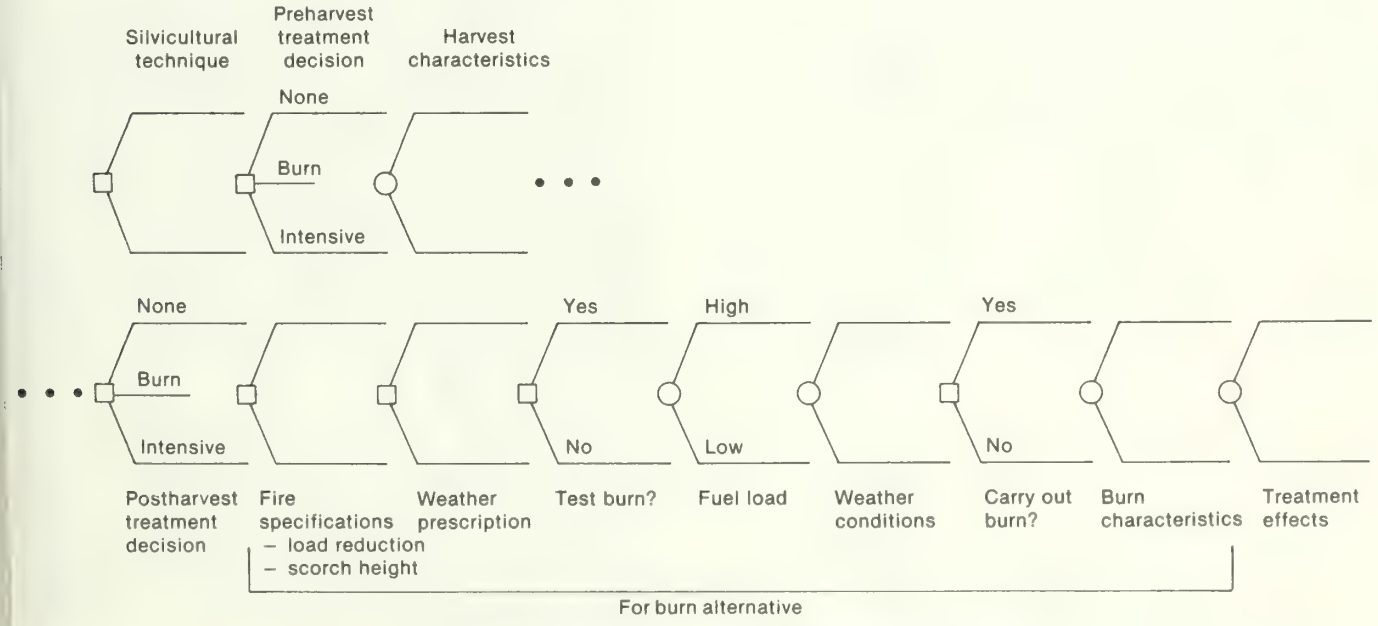


Figure 14.—Sequence of harvest and treatment decisions.

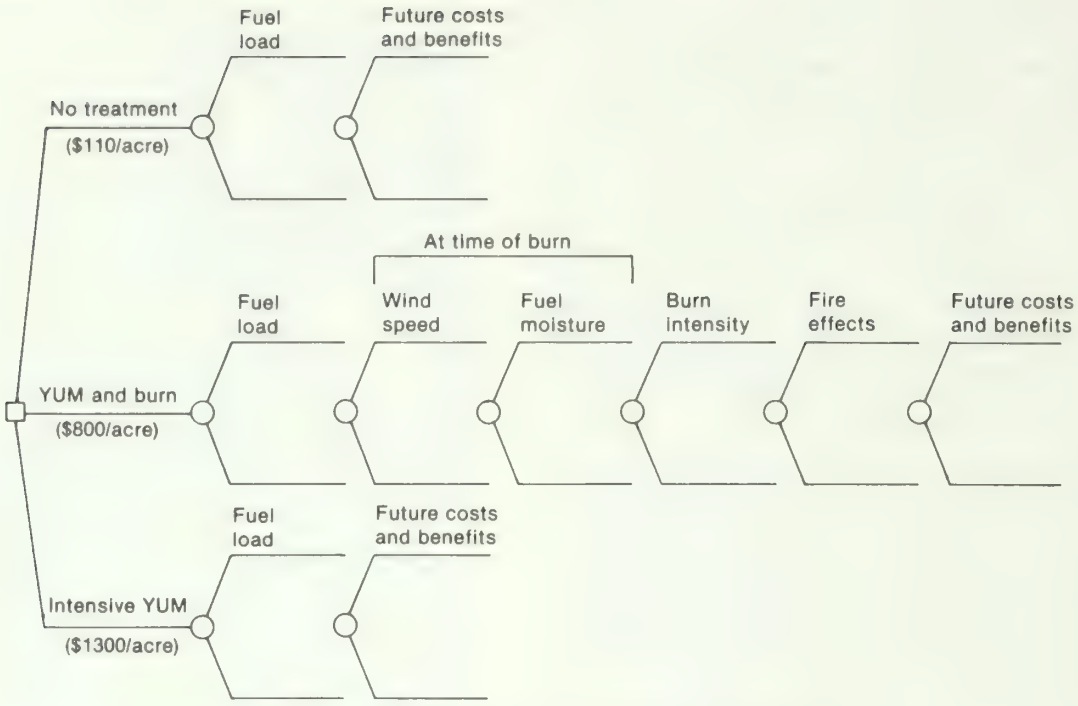


Figure 15.—Structure of postharvest fuel treatment decision.

Fire Intensity.—A second critical uncertainty for the prescribed burn alternative is the severity of the burn. Although a large number of fire characteristics interact in a complex manner with various site factors to determine the results of a fire, we have chosen to integrate many of these factors using predicted fireline intensity (Bryam 1959) as an index of potential burn severity. Several previous evaluations of fire management activities have also expressed potential fire effects as conditional on fireline intensity (Hirsch et al. 1979, Schweitzer et al. 1982, U.S. Department of Agriculture Forest Service 1980a). Modeling uncertainty in fireline intensity was carried out in three steps, the first two of which are described here and the third in the following subsection.

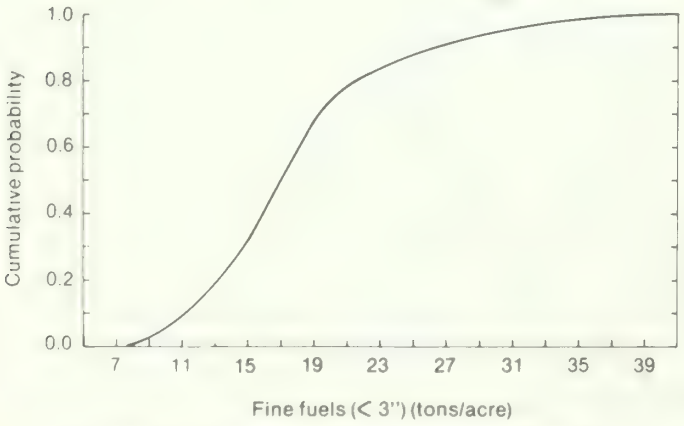


Figure 16.—Uncertainty in postharvest fuel load.

The three steps involve:

1. Explicitly characterizing the uncertainties in fuel moisture, wind speed, and fire behavior predictions.
2. Combining the three uncertainties with the predicted fire intensities (given as a function of fuel load, fuel moisture, and wind speed) to produce cumulative probability distributions describing fire intensity given the fuel load.
3. Combining the cumulative distributions on fire intensity with assessments of both acceptable intensity ranges and the ability of the burn crew to compensate for nonoptimal weather conditions to produce discrete probability distributions on the outcomes.

Predictions of fire intensity given wind speed and fuel moisture were provided by an existing fire behavior model (Rothermel 1972). An example of the output from this model is shown in figure 18 for the case with a fine fuel loading of 27 tons per acre. Uncertainty in the predicted intensity as a result of model and data approximations is represented in the top node of figure 19 (Albini 1976).

The weather prescription for a broadcast burn includes the range of acceptable wind speed and fuel moisture conditions. The actual conditions at the time of burn are, within this range, uncertain from the perspective of the individual making the treatment method decision. The bottom two nodes in figure 19 reflect the uncertainty likely to be present, based on the judgment of the Mount Hood National Forest fuels specialist.

Uncertainties in fire behavior predictions, fuel moisture, and wind speed were factored together with the fire behavior model output to produce cumulative probability distributions for intensity, given fuel loading. Each combination of fuel loading, model variation, wind speed, and fuel moisture resulted in an intensity figure and associated probability of occurrence. These intensities and probabilities were combined to produce the three distributions shown in figure 20, one for each separate fuel loading level. These distributions reflect all three uncertain factors (assumed to be mutually independent) shown in figure 19.

Compensation Capability and Acceptable Intensity Range.—The fire intensities just discussed leave out one important factor: the ability of firing crews to compensate for existing wind and fuel moisture conditions by varying the ignition pattern and burn technique. To a limited extent, the crews have the capability (e.g., by adjusting ignition strip width) to increase the severity of a fire running too cold and to decrease the severity of an overly hot fire. This capability is important in achieving the fuel reduction objectives while minimizing damage to the duff and residual white pine. The extent of such capability is uncertain and varies according to specific situations. Rather than trying to represent this uncertainty for the specific site, which would provide few insights for a broader class of treatment decisions, we have chosen to model the compensation (or control) capability together with the range of acceptable burn intensities through a set of decision scenarios.

This latter characteristic—the acceptable burn intensity—is an additional site-specific characteristic. A burn too cold will not achieve the desired reduction in fine fuels, but the acceptable limit depends on the site characteristics and the objectives of the burn. In situations for which damage to duff or remaining overstory must be controlled, there is a threshold on the high-intensity side as well. The acceptable range can be represented by an interval, or "window," on the fireline intensity scale shown in figure 20. A burn whose intensity falls within this window produces minimum posttreatment costs. The potential costs caused by the fire hazard of the remaining fuels increase below the interval. The costs of damage to duff and, in the specific example, white pine, increase above the interval. This is a discrete-step approximation to a continuous relationship where effects are a function of intensity. Thus, the burn alternative is modeled as having four possible outcomes: the three just mentioned plus the chance of the fire escaping prescription and spreading into adjacent areas not scheduled for burning.

Using the representation just discussed, the intensity control capability is represented by specifying the acceptable range of predicted (without compensation) intensities, which, assuming effective compensation measures, will result in the actual intensity's falling within the acceptable range. The predicted intensity window is, therefore, as wide or wider than the actual intensity window, depending on the effectiveness of

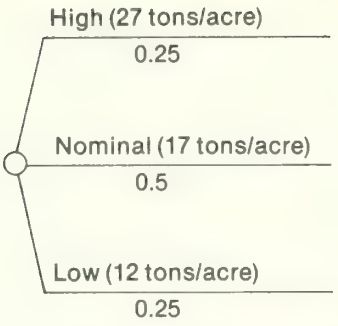


Figure 17.—Discrete representation of uncertainty in fuel load.

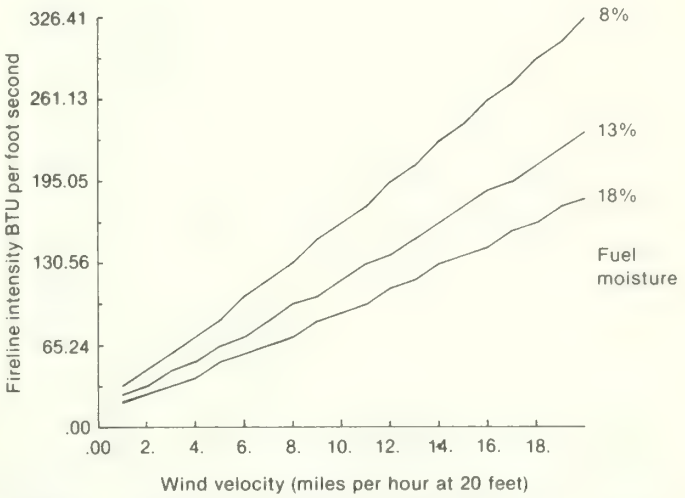


Figure 18.—Sample fire behavior model output for fine fuel loading of 27 tons per acre.

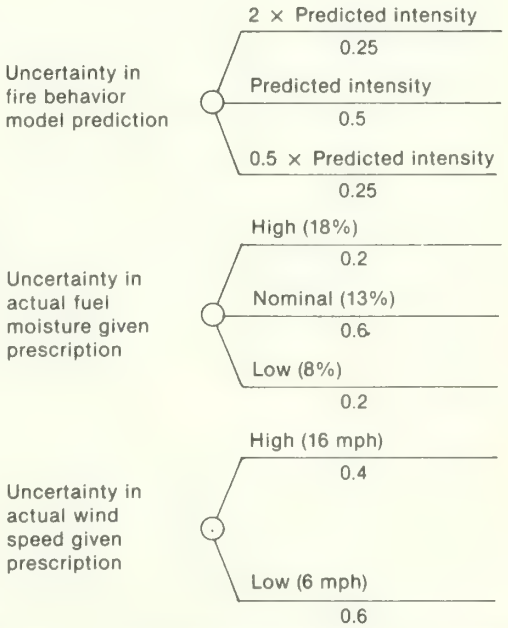


Figure 19.—Factors inducing uncertainty in fire intensity.

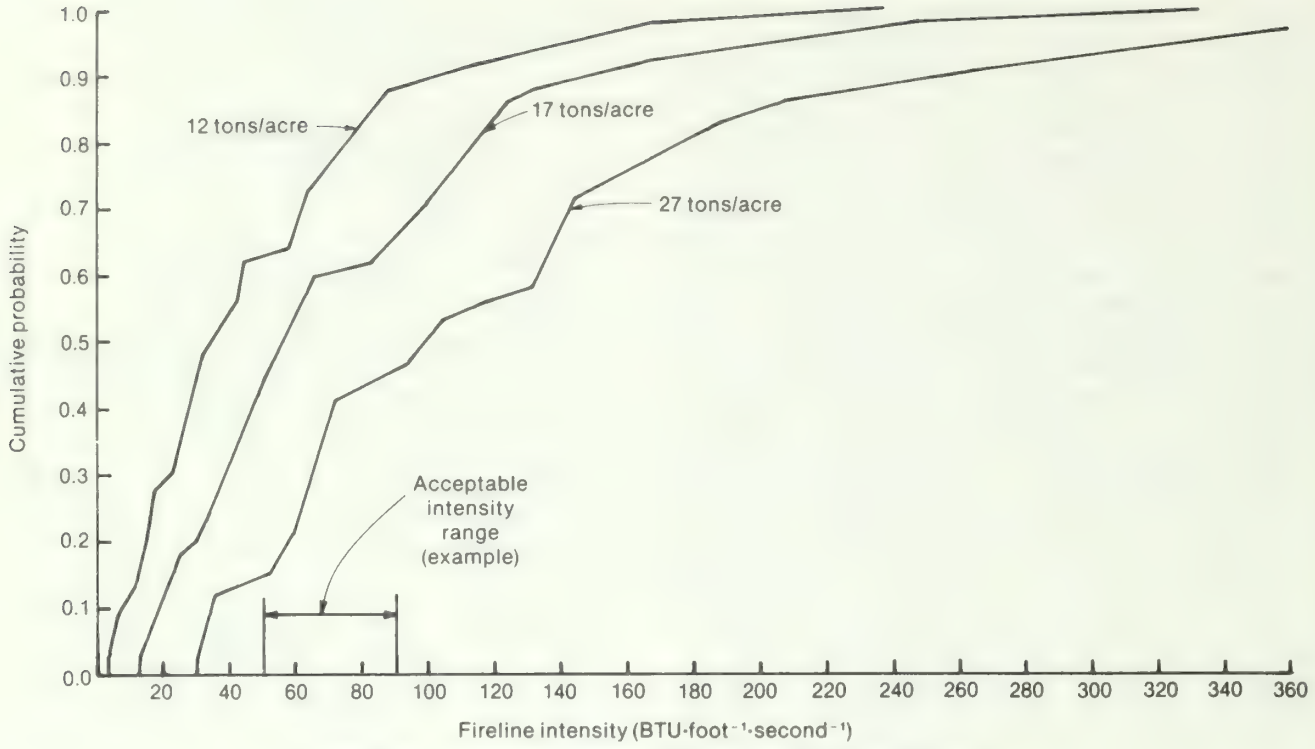


Figure 20.—Predicted intensity of prescribed fire given uncertainty in wind, fuel moisture, and fire behavior predictions (prior to burn compensation).

compensation measures. The four generalized decision scenarios used in this analysis are summarized in table 6a. The relationship between the four scenarios and the various combinations of acceptable intensity ranges and control capabilities is shown in table 6b. Essentially, we have tried to approximate a dozen specific scenarios through four generalized scenarios with progressively broader intensity tolerance ranges. The alternatives available are the same for each decision scenario: Should a broadcast burn, an intensive treatment, or no treatment be selected? Note that two specific combinations did not fall within any of the generalized scenario ranges listed in table 6a. These combinations were not addressed in the analysis.

Intensity windows associated with each decision scenario were superimposed on the three continuous probability distributions of figure 20 to produce the discrete distributions shown in table 7. Accurately predicting the chance of a fire escaping prescription is critical. To check this sensitivity, two modified scenarios (1a and 3a), incorporating a greater probability of escape, were created from decision scenarios 1 and 3. Outcome distributions for these two scenarios are listed in table 8.

Costs and Benefits.—The approach taken in assigning costs and benefits was to assume that the objective of the treatment decision is to minimize the costs and losses that must be subtracted from a constant, nominal level of benefit. Three cost categories were defined: the cost of implementing the selected fuel treatment (decision cost), the expected posttreatment cost from the potential fire hazard (fire hazard cost),

Table 6a.—Generalized decision scenarios for the fuel treatment decision

	Compensated (actual) acceptable intensity range (Btu·foot^{-1}·second^{-1})	
Scenario	**Low end**	**High end**
1 (narrow tolerance range)	50-55	95-100
2 (moderate tolerance range)	35-45	100-115
3 (wide tolerance range)	25-35	120-155
4 (very wide tolerance range)	20-25	170-225

Table 6b.—Relationships among decision scenarios[1]

	Acceptable range of actual intensities[2] (Btu·foot^{-1}·second^{-1})		
Control capability	**Wide (40-100)**	**Nominal (50-90)**	**Narrow (60-80)**
Can compensate for +/−5 mph wind speed	Scenario 3 [3](33-120)	Scenario 2 (42-180)	Scenario 1 (50-96)
Can compensate for +/−10 mph wind speed	--- (16-250)	Scenario 4 (20-225)	Scenario 4 (24-200)
Can compensate for +/−5% fuel moisture	Scenario 3 (25-140)	Scenario 3 (31-126)	Scenario 2 (38-112)
Can compensate for +/−5 mph wind speed and +/−5% fuel moisture	Scenario 4 (21-170)	Scenario 3 (26-153)	Scenario 3 (32-136)
No compensation capability	Scenario 2 (40-100)	Scenario 1 (50-90)	--- (60-80)

[1] *Decision scenarios are defined in table 6a.*
[2] *To minimize damage to remaining overstory.*
[3] *Acceptable range of predicted intensities prior to compensation (Btu·foot^{-1}·second^{-1}).*

and the cost from damage to the white pine seed trees (white pine cost). The white pine cost applies only to the prescribed burn alternative. The white pine stands are analogous to any resource present in a treatment decision problem that suffers increasing damage as the intensity of the prescribed burn increases. All costs are expressed in terms of dollars for the 25-acre site.

Fire hazard costs were calculated using the annual cost-plus-NVC model developed in the budget-level analysis. Suppression cost and resource value change data for this model are given in the appendix. Each fuel reduction outcome from the treatment decision (cold, nominal, hot, or escape for the burn alternative; and low, nominal, or high fuel reduction for the 6×6 YUM alternative) was represented by a posttreatment fire hazard class in the cost-plus-NVC model. For the burn alternative, these hazards correspond roughly to stylized fuel models 12 (medium slash), 11 (light slash), and 8 (closed timber litter) (Albini 1976). Output, given expected annual NVC for each hazard class, expressed on a per acre basis, was then scaled by the number of acres in the treatment site to estimate the annual expected fire losses for the site, given the treatment outcome. A 20-year stream of the expected annual values was then discounted to the present value to produce the nominal fire hazard costs. A discount rate of 10% was used. The nominal values, along with sensitivity ranges, are shown at the top of table 9. The costs of an escaped fire were similarly calculated by scaling the average cost of one such fire as calculated by the cost-plus-NVC model.

White pine damage costs are based on the assumption that the greater the intensity of a prescribed burn, the greater the pine mortality, which implies less capability of the white pine to initiate regeneration and necessary hand planting, reseeding, and fertilizing. Costs used (shown in table 9) are based on discussions with Clackamas District staff. The actual costs can vary from site to site. For this reason, several cost assumptions were examined in the value of information analysis discussed in the following paragraphs.

The decision costs were expressed earlier on a per-acre basis. For the entire 25-acre site, the estimated costs of carrying out each alternative are as follows:

No treatment	$ 2,500
YUM and burn	$20,000
YUM 6×6	$32,500

Analysis Under Uncertainty.—Analysis of the treatment decision produced a startling result: The no-treatment alternative was dominant, regardless of the decision scenario or cost assumption. This led to three possible conclusions:

1. There are benefits from fuel treatment considerably in excess of those explicitly quantified in this analysis.
2. Because of poor access, the costs of treatment for the studied site are much greater than for the average site.
3. Much more treatment activity is being carried out than is economically justified.

Table 7.—Probability distributions on outcome of prescribed burn, given fuel load and decision scenario

Scenario[1]	Outcome	Fuel loading		
		Low	Nominal	High
1	Cold	0.63	0.44	0.14
	Nominal	0.27	0.27	0.33
	Hot	0.10	0.28	0.46
	Escape	0.00	0.01	0.07
2	Cold	0.54	0.31	0.13
	Nominal	0.37	0.46	0.38
	Hot	0.09	0.22	0.42
	Escape	0.00	0.01	0.07
3	Cold	0.44	0.20	0.03
	Nominal	0.51	0.69	0.61
	Hot	0.05	0.10	0.29
	Escape	0.00	0.01	0.07
4	Cold	0.29	0.11	0.00
	Nominal	0.70	0.83	0.80
	Hot	0.01	0.05	0.13
	Escape	0.00	0.01	0.07

[1]*Decision scenarios are defined in table 6a.*

Table 8.—Outcome distributions for modified decision scenarios

Decision scenario[1]	Outcome	Fuel load		
		Low	Nominal	High
1(a)	Cold	0.62	0.44	0.14
	Nominal	0.25	0.25	0.32
	Hot	0.08	0.26	0.44
	Escape	0.05	0.05	0.10
3(a)	Cold	0.43	0.20	0.03
	Nominal	0.49	0.67	0.60
	Hot	0.03	0.08	0.27
	Escape	0.05	0.05	0.10

[1]*Created from generalized scenarios 1 and 3 of table 6a, allowing a greater probability of escape.*

Table 9.—Cost components (dollars/25 acres)

Outcome	Sensitivity range		
	Low	Nominal	High
		Fire hazard	
Cold (or low reduction)	500	1,000	5,000
Nominal	100	200	1,000
Hot (or high reduction)	50	100	500
Escape	15,000	30,000	75,000
		White pine[1]	
Cold	0	0	0
Nominal	1,500	3,000	15,000
Hot	7,500	15,000	75,000
Escape[2]	5,000	10,000	50,000

[1]*White pine damage costs are zero for all outcomes of the no treatment or intensive treatment alternatives.*

[2]*White pine costs given the escape outcome are relatively low to avoid double counting with the fire hazard costs.*

A hypothesis supporting conclusion 1 is that the cumulative effect of choosing the no-treatment alternative on a regular basis would be to greatly increase the expected fire hazard. To test this hypothesis, the cost-plus-NVC model developed for the budget analysis was again used. An extended period during which little fuel treatment was carried out would result in a considerably increased amount of area with a fire hazard represented by a slash type of stylized fuel model. This is reflected in the high slash case used in the budget level analysis. The per-site fire hazard (expected annual cost + NVC) is increased significantly by the cumulative effects of no treatment: The costs almost double. However, the increase is not enough to lead to another alternative's being preferable.

Another possible explanatory factor is that significant benefits accrue to fuel treatment as a result of considerations other than fire hazard reduction and seedbed preparation. These might include, for example, watershed and wildlife values, or enhanced esthetics.

It is often the case that the no-treatment option is unacceptable because of silvicultural regulations: The site is required to be restocked within 5 years. This should properly be considered a site-preparation decision rather than a fuel-treatment decision.

The second possible conclusion is clearly true as far as it goes, but decreasing the costs of the treatment alternatives (say, by 50%) does not change the dominance of the no-treatment alternative. The analysis showed that for one of the more intensive treatment alternatives to be optimal, all of the following must be true:

1. The cost of the treatment alternative must be lower by at least 50%.
2. The fire hazard costs must be at the high end of their range.
3. White pine damage costs (or other resources that may be damaged while carrying out fuel treatment) must be relatively low.

For the wide range of cases in which the no-treatment alternative is preferred, there is no value in reducing uncertainty in fuel load or in the outcomes of the other alternatives. For the purposes of the remainder of this analysis, it was assumed that some combination of conclusions 1 and 2 is descriptive of the situation. The no-treatment alternative was not considered further in the value of information analysis.

Value of Information Analysis

Figure 21 shows the decision tree on which the detailed analysis of the value of information was based. Note that the no-treatment option has been omitted. Probabilities for the outcomes given the burn alternative are not displayed; they depend on the decision scenario (tables 7 and 8).

Examination of the total nominal cost column of figure 21 highlights the difference between the two alternatives. The burn alternative is less expensive to

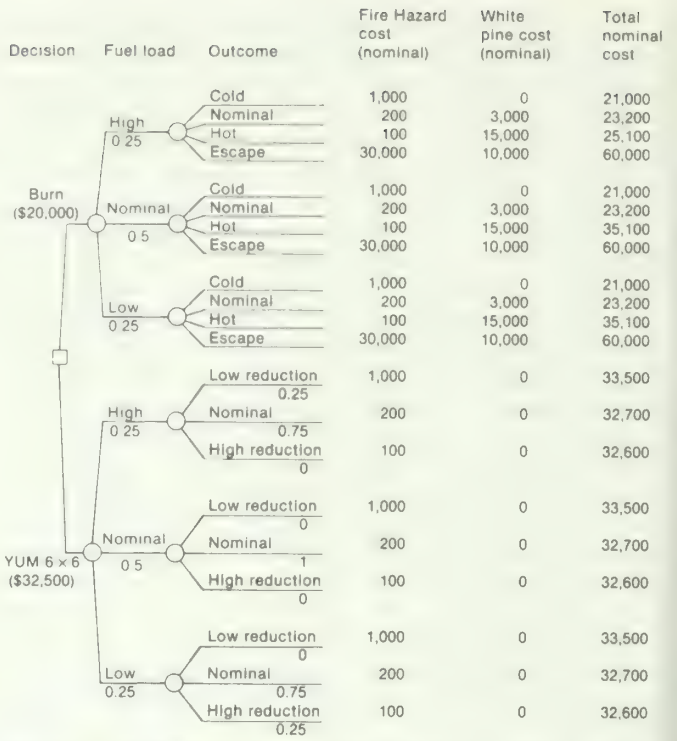


Figure 21.—Decision tree for treatment decision value of information analysis.

carry out and may have a relatively low cost outcome, but it may also have a very costly outcome; the variability in its cost is relatively high. In contrast, the variability in the cost of the intensive treatment alternative (YUM 6×6) is extremely low, but the initial (and minimum) cost is considerably higher. One must balance the uncertainty in one case with the known higher costs in the other. This is a natural situation in which to explore the economic value of reductions in uncertainty.

For all six decision scenarios using nominal costs, the preferred alternative is the broadcast burn. As the white pine or fire hazard costs increase or the decision costs decrease, the optimal alternative shifts to the intensive YUM treatment. The point at which the decision under uncertainty shifts depends on the decision scenario.

The value of information analysis was carried out by calculating the EVPI on postharvest fuel loading for each decision scenario while varying the fire hazard, white pine, and decision costs. Results of the analysis are summarized in figures 22a through 22d. In each figure, the EVPI on fuel loading is plotted on the vertical axis, while the cost component being varied is plotted on the horizontal axis. Figures 22a and 22b assume costs of the treatment alternatives as defined for the specific site under study. Treatment costs that are lower by 50% are assumed in figures 22c and 22d and may more accurately reflect a majority of fuel treatment decisions (because of the increased cost resulting from poor access to the specific site examined).

Figure 22a shows how the EVPI on postharvest fuel load varies among decision scenarios over a range of white pine damage costs. The results for scenario 2,

although not shown directly, are similar to those for scenario 1. The general pattern reflects the dominance of the burn alternative when white pine costs are low and the dominance of the intensive treatment alternative when white pine costs are very high. For intermediate cost levels the choice is not clear, thus the EVPI is greatest. The EVPI is nonzero at nominal white pine damage costs only for decision scenario 1a, for which it is assumed that the acceptable intensity range is narrow, control capability is limited, and the probability of fire escaping prescription is relatively high. As one moves from scenario 1 through 3 to 4, note that the EVPI decreases for white pine costs in the range of nominal to twice nominal. This is due to the increasing preference for the burn alternative as the acceptable intensity range and/or control capability increases. Finally, note that the cases with high escape probability (scenarios 1a and 3a) have lower maximum EVPI values but have greater EVPI (than scenarios 1 and 3) at the lower (and more realistic) cost levels.

In figure 22b, the EVPI on fuel loading is plotted against the posttreatment fire hazard costs. While the plots look considerably different, three patterns analogous to those of figure 22a are found. First, for all decision scenarios, the EVPI increases up to some point as the fire hazard cost component increases. Second, as the tolerance range for intensity assumed in the decision scenario increases (moving from scenario 1 to 4), the EVPI on fuel load decreases for a given level of fire hazard cost. Finally, assuming relatively high probabilities of a fire's escaping prescription (scenarios 1a and 3a) leads to an increase in the EVPI at the lower (and again more realistic) levels of the fire hazard cost.

Figure 22c shows the variation in fuel loading EVPI as white pine costs are changed for scenarios in which it is assumed that the costs of the treatment alternatives are one-half of the nominal (site-specific) values. (Specifically, YUM (8×10) and burn at $400 per acre or intensive (6×6) YUM at $600 per acre.) Scenarios 2 and 3 have plots similar to that for scenario 1. One immediately notices that both the maximum EVPI and the range of white pine costs over which the EVPI is nonzero are decreased from the nominal decision cost cases (fig. 22a). Of perhaps greater importance, the EVPI on fuel load for white pine damage costs of from one-half to one-and-one-half of nominal is considerably greater than was found for the nominal decision. At the nominal white pine damage cost level, EVPI on fuel loading ranged from about $200 to $1,000 for the 25-acre site, depending on the decision scenario. In this set of cases, with the costs of implementing the alternative treatment methods being perhaps closer to those found in a majority of treatment decisions, the scenarios with high probability of escaped fires have generally lower EVPI. This behavior reflects the dominance of the intensive treatment alternative when faced with such high escape probabilities. Better fuel information would only rarely change the decision.

EVPI on fuel loading as a function of fire hazard cost for the case with lower decision costs is shown in figure 22d. Again, scenario 2 is similar to scenario 1. It is interesting to contrast these plots with those for the nominal decision costs in figure 22b. The maximum EVPI is achieved at much lower assignments of fire hazard cost for each decision scenario. In particular, the value of perfect information at the nominal fire hazard cost point is significant, ranging from $500 to $1,000 for the basic scenarios. The modified scenarios (with higher probability of a fire's escaping prescription) result in generally lower EVPI values, reflecting the dominance of the low-variance, intensive treatment option for such scenarios. In comparison with figure 22c, one notes that the EVPI is relatively high for a wide range of hazard costs in figure 22d. Fire hazard cost is a major consideration regardless of the alternative chosen, while white pine damage is risked only for the burn alternative.

The Value of Imperfect Information

The information values discussed above represent the expected values of perfect information. Equivalently, the EVPI gives the economic value of totally eliminating the uncertainty inherent in the information of the fuels management specialist. Clearly, such a complete elimination of uncertainty is impossible (or at least very expensive) in the context of postharvest loading of fine fuels.

To investigate the value of reducing—but not eliminating—uncertainty, EVPI was calculated on fuel load for a variety of cases in which the variance in the initial probability distribution was reduced by about 60%. This led to EVPI values in the range of 30-50% of those plotted in figures 22a through 22d. The variation in EVPI with respect to the decision scenarios and cost components was analogous to the original cases.

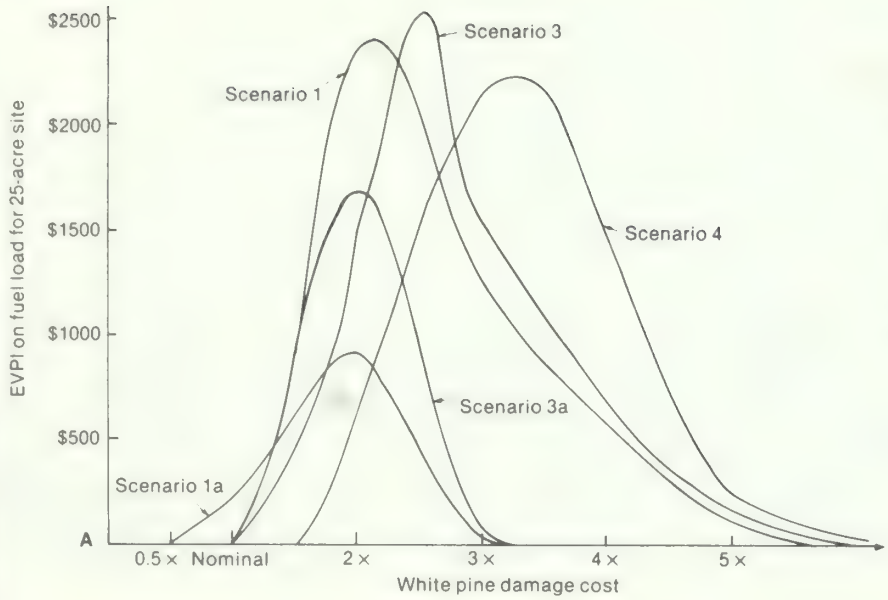
This analysis suggests that the value of improved but not perfect information might be on the order of one-half to two-thirds of the EVPI. Such reduced information values are most appropriate for use in guiding the allocation of information-gathering resources.

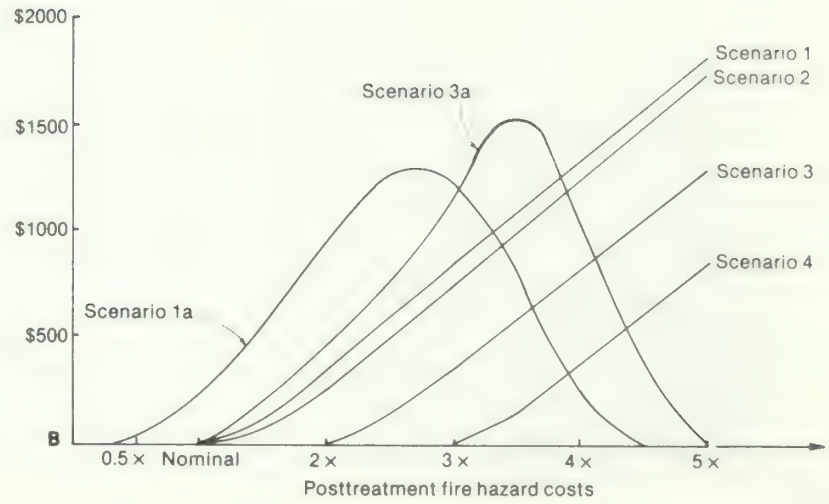
Summary and Recommendations

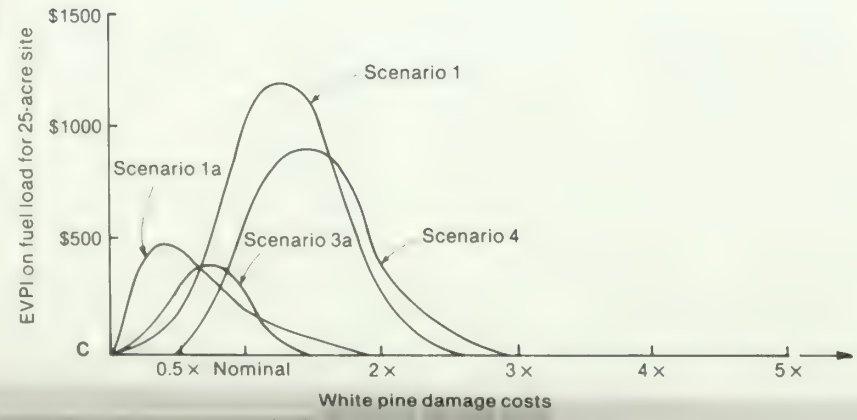
For the site-specific decision as orginally defined, the no-treatment alternative was clearly dominant. Even when the costs of treatment are reduced by half, to levels that more closely approximate many treatment decisions, the no-treatment alternative is still preferable. For the reduced treatment cost decision problem, decreasing fire hazard or white pine damage costs could lead to one of the treatment options being superior.

In light of the above observations, more research is necessary to either:

1. Determine the cumulative fire hazard cost, wildlife benefits, or other factors that justify carrying out fuels treatment activities on a majority of harvest sites, or







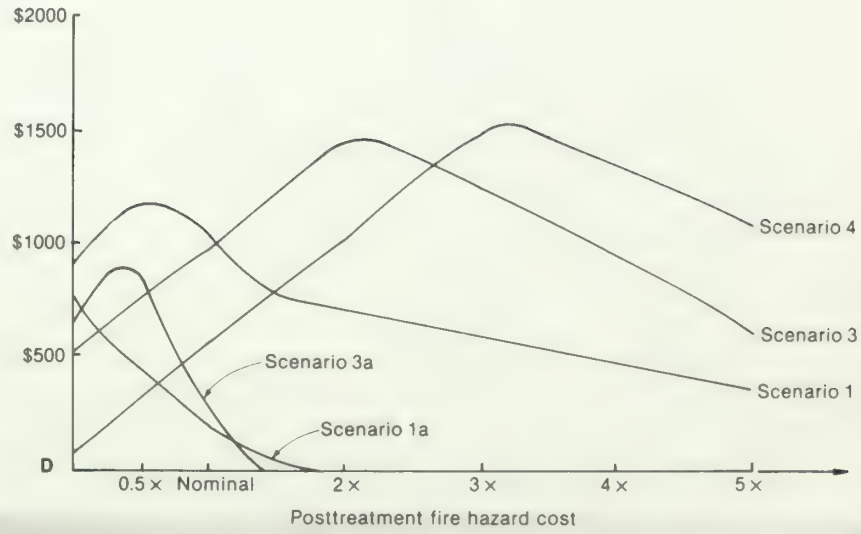


Figure 22.—EVPI on fuel load, (A) as a function of white pine cost; (B) as a function of fire hazard cost; (C) as a function of white pine cost, for scenarios with one-half nominal treatment costs; and (D) as a function of fire hazard cost, for scenarios with one-half nominal treatment costs. Scenarios are defined in tables 6a and 8.

2. Demonstrate that the values defined in (1) are insufficient to justify, on an economic basis, the amount of fuel treatment activity presently being done.

In treatment decisions for which the no-treatment alternative is not dominant (or when it has been decided that some treatment is necessary, based on other factors), some effort devoted to gathering information on postharvest fuel load may be worthwhile. Using the most likely scenarios, the expected value of perfect information on fuel load fell between $300 and $800 for a 25-acre site ($12 to $32 per acre). Information that could be expected to reduce uncertainty (perhaps reducing the variance of the probability distribution on the loading of fine fuels by 50-75%) would be worth $100 to $400 ($4 to $16 per acre). Accounting for all costs, this suggests that in many cases it would be worthwhile to invest one to two person-days in developing an improved estimate of postharvest fuel load before making the final treatment decision.

It is worth noting that improved information could have value beyond reducing uncertainty in the aggregate mass of fine fuels. Better understanding of the breakdown of fuels by size class and type could be used as input to an improved fire behavior model to obtain better predictions of the characteristics of prescribed fires. The same information would also be useful in carrying out the treatment option ultimately selected and in assessing the effectiveness of treatment.

The recommendations derived from this study can be summarized as follows:

1. Careful thought should be given to the no-treatment alternative in more instances. Improved exchange of information among fuel management, silviculture, wildlife, recreation, and other specialists would help in resolving this issue.
2. For harvest sites having important resources that are sensitive to damage from a burn or for sites having poor access leading to high treatment costs, the more expensive hand treatment options may be worthwhile.
3. For the many cases in which broadcast burning is likely to be a good alternative but for which some resource values may be sensitive to excessive high or low burn intensities, it is probably worth investing one or two person-days in improving the fuel information base prior to making the final treatment decision.

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APPENDIX

BASE CASE AND SENSITIVITY DATA

General

The following data represent the Clackamas and Estacada districts of the Mount Hood National Forest:

Nominal budget	(*dollars/year*)
Prevention	58,000
Presuppression and initial attack	208,000
Fuel treatment and brush disposal	477,000
Total	743,000
Ignitions	(*average number/year*)
Industrial	1
Other human-caused	25
Lightning	8
Nominal area distribution: fuel types	(*acres*)
Total area	400,000
Timber litter plus understory (model 10)	280,000
Timber litter (model 8)	80,000
Heavy slash (model 13)	20,000
Medium slash (model 12)	20,000

Intensity Distribution

Table A-1 gives the discrete probability distributions for fireline intensity (Byram 1959) given the fuel model type in which a fire starts. Intensity classes are defined as follows:

Intensity class	Btu·foot^{-1}·second^{-1}
Low	0–100
Medium	100–700
High	>700

The data in the table are based on the cumulative probability distributions generated by the Rothermel (1972) fire behavior model using historical weather data (Furman and Brink 1975) for the case study area. (A sample model run is shown in fig. A-1.)

Table A-1.—Probability distributions for fireline intensity class given fuel type at fire origin

	Intensity class		
Area type of fire start	Low	Moderate	High
Heavy slash (13)	0.00	0.28	0.72
Medium slash (12)	0.03	0.61	0.36
Timber litter (8)	1.00	0.00	0.00
Litter + understory (10)	0.78	0.19	0.03

Escape Fractions

The fraction of fires escaping initial attack (or, equivalently, the probability that a fire escapes) is conditional on fireline intensity. The following escape fractions are based on the judgment of Mount Hood fuels and fire management staff: low intensity, 0.0; moderate intensity, 0.3; and high intensity, 0.8.

Size Distribution

Table A-2 gives the individual probability distributions for fire size class, given area type (stylized fuel model type) at the fire's origin, intensity class, and escape/control status. The distributions are based on the judgment of Mount Hood fuels and fire management staff. An iterative process was used whereby the implications of an initial set of distributions were examined to refine the assessments.

Resource Value Changes

Expected changes in resource value caused by fire are listed in table A-3, expressed in terms of dollars per acre. Values given are based primarily on timber resources and cost of rehabilitation; implications of assigning greater values based on nonmarke

esources are examined in the sensitivity analysis and value of information subsections. Timber values and rehabilitation costs used are based on recent experience of the Mount Hood National Forest.

NVC values are a function of fire size, intensity, and location. Fires in the lowest intensity range have very low expected value changes. Small fires starting in slash are also assigned small values, as such fires have little resource impact. Larger fires starting in slash areas are expected to have spread into timber, implying greater timber damages.

Table A-2.—Fire size probability given area type and intensity class

Fire type / Intensity class	Size class: 0.1 average acres	10 average acres	100 average acres	1,000 average acres
Controlled fires		All area types		
Low	0.95	0.05	0.00	0.00
Moderate	0.80	0.20	0.00	0.00
High	0.60	0.40	0.00	0.00
Escaped fires		Area type: Heavy slash (13)		
Low	0.20	0.80	0.00	0.00
Moderate	0.10	0.70	0.19	0.01
High	0.00	0.80	0.18	0.02
		Area type: Medium slash (12)		
Low	0.40	0.60	0.00	0.00
Moderate	0.20	0.60	0.19	0.01
High	0.00	0.80	0.18	0.02
		Area type: Timber litter (8)		
Low	1.00	0.00	0.00	0.00
Moderate	0.20	0.60	0.20	0.00
High	0.00	0.80	0.19	0.01
		Area type: Litter + understory (10)		
Low	1.00	0.00	0.00	0.00
Moderate	0.20	0.60	0.19	0.01
High	0.00	0.80	0.18	0.02

Table A-3.—Expected resource value changes in dollars per acre

ntensity class	Size class: 0.1 average acres	10 average acres	100 average acres	1,000 average acres
		Area type: Heavy slash (13)		
ow	200	200	200	200
loderate	500	500	1,000	1,000
igh	500	750	1,200	1,200
		Area type: Medium slash (12)		
ow	200	200	200	200
loderate	500	500	1,000	1,000
igh	500	750	1,200	1,200
		Area type: Timber litter (8)		
ow	200	200	200	200
loderate	1,000	1,500	1,500	1,200
igh	1,500	2,000	2,000	2,000
		Area type: Litter + understory (10)		
ow	200	200	200	200
loderate	1,000	1,500	1,500	1,200
igh	1,500	2,000	2,000	2,000

Suppression Costs

Suppression costs for fires escaping initial attack are shown in table A-4. These costs are based on experience of the Mount Hood and other forests in the Pacific Northwest Region. It is assumed that all fires of the smallest size class are controlled by initial attack forces. Costs are given in average dollars per acre per fire.

Table A-4.—Expected suppression costs for fires that escape initial attack (dollars per acre)

Intensity class	Size class: 0.1 average acres	10 average acres	100 average acres	1,000 average acres
Low	0	500	500	500
Moderate	0	500	500	500
High	0	500	500	500

Sensitivity Test Data

Table A-5 shows the distribution of area among the four fuel types for three fuel scenarios: high slash, nominal slash, and low slash. In table A-6, fireline intensity distributions are given for scenarios involving twice-nominal intensities and half-nominal intensities.

Table A-5.—Distribution of land area (thousands of acres) among the four fuel model types for three fuel scenarios

Fuel scenario	Fuel model type: 13	12	8	10
High slash	40	80	200	80
Nominal	20	20	280	80
Low slash	10	10	280	100

Table A-6.—Intensity class probabilities for fire behavior scenarios involving twice-nominal and half-nominal fireline intensities

Area type of fire start	Intensity class: Low	Moderate	High
Intensity distribution with two times intensities			
Heavy slash (13)	0.05	0.41	0.54
Medium slash (12)	0.13	0.60	0.27
Timber litter (8)	1.00	0.00	0.00
Litter + understory (10)	0.81	0.17	0.02
Intensity distribution with one-half times intensities			
Heavy slash (13)	0.00	0.14	0.86
Medium slash (12)	0.01	0.48	0.51
Timber litter (8)	0.50	0.50	0.00
Litter + understory (10)	0.39	0.48	0.13

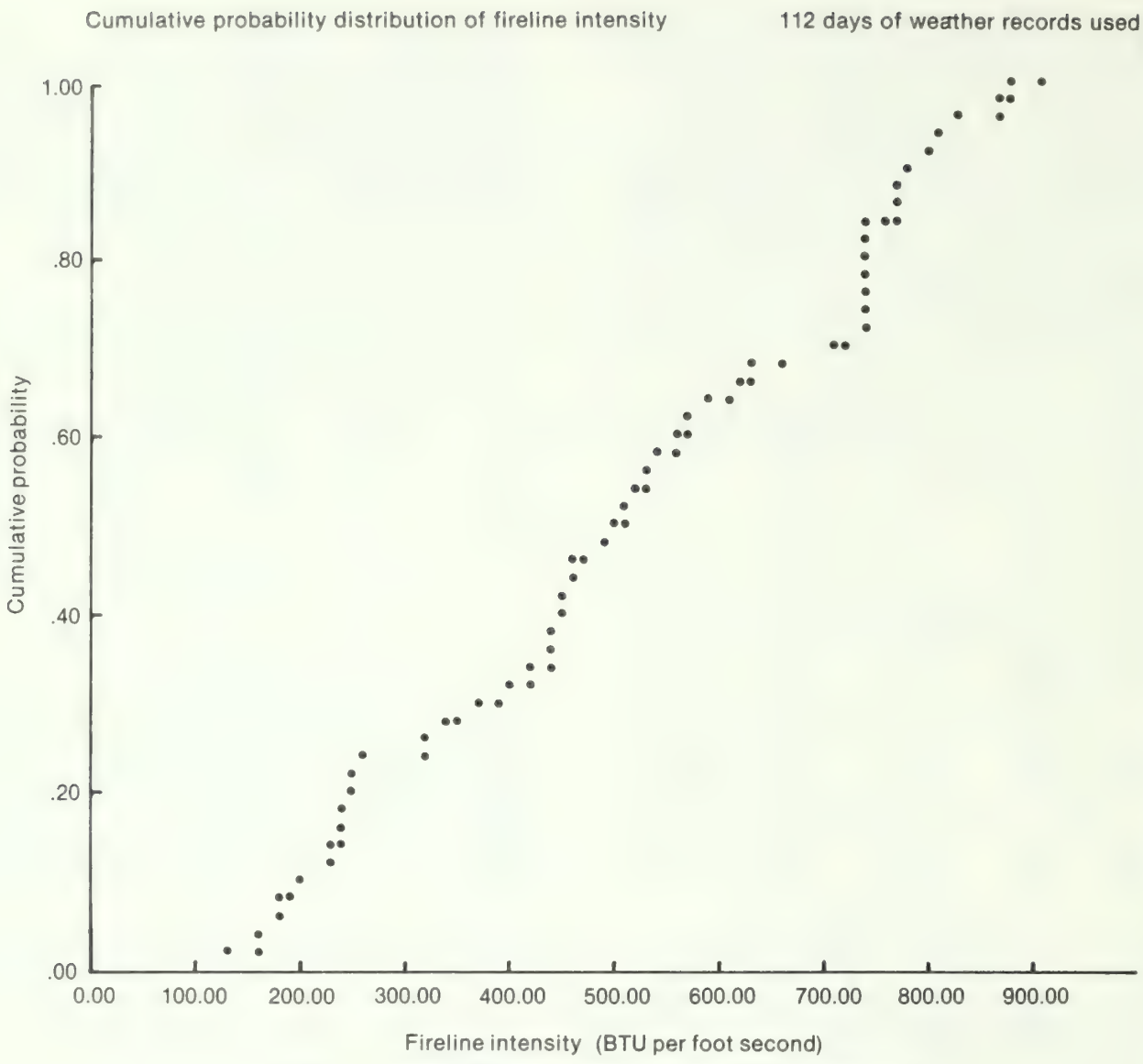

Figure A1.—Sample FIREBHV output (fuel model 12, Ripplebrook Fire Weather Station).

Barrager, Stephen M., David Cohan, and Peter J. Roussopoulos. 1982. The economic value of improved fuels and fire behavior information. USDA Forest Service Research Paper RM-239, 32 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

The development and case study application of a method for determining the economic value of improving fuel and fire behavior information for fire management decisionmaking is presented. Two routine decisions are analyzed on the Mount Hood National Forest—the annual fire management budget request and a site-specific fuel treatment decision.

Keywords: Decision analysis, wildfire protection, economic efficiency, fuel treatment, prescribed fire

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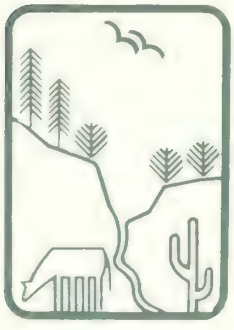
Rocky Mountains



Southwest

Great Plains

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Bottineau, North Dakota
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Lubbock, Texas
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526

Effects of Partial Cutting on Diseases, Mortality, and Regeneration of Rocky Mountain Aspen Stands

James W. Walters, Thomas E. Hinds,
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Effects of Partial Cutting on Diseases, Mortality, and Regeneration of Rocky Mountain Aspen Stands

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Abstract

Logging wounds on residual aspen, in partially cut stands, predisposed wounded trees to attack by insects and diseases. Five to 7 years after cutting, aspen mortality amounted to 20%; 41% of the live trees were infected with canker diseases; and 30% were infested with wood borers. Adequate sprouting occurred even though only 60-80% of the basal area was removed.

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[2] *Headquarters is in Fort Collins, in cooperation with Colorado State University.*

Effects of Partial Cutting on Diseases, Mortality, and Regeneration of Rocky Mountain Aspen Stands

James W. Walters, Thomas E. Hinds, David W. Johnson, and Jerome Beatty

Management Implications

Partial cutting in aspen, such as selection and shelterwood cutting, may have detrimental effects on the residual trees and may not be a desirable method of harvesting aspen stands. Tree wounds, common with usual logging practices, can become infected with canker diseases, which in this study killed 20% of the residual trees several years after logging. Additional infections remain on the trees causing continued mortality and making them more susceptible to wind breakage. Once a stand is opened by logging, increased sunscald and infestations by boring insects weaken residual trees. Removal of 60% to 80% of the basal area will still insure adequate sprouting to maintain the aspen type. However, the remaining overstory will eventually degenerate to the point of being worthless for timber harvest.

Introduction

Quaking aspen (*Populus tremuloides* Michx.) stands in the Rocky Mountain States occupy about 4.1 million acres of commercial forest land and contain an estimated 7.3 billion board feet of sawtimber (Green and Setzer 1974). Because many western aspen stands are mature or overmature, efforts to harvest them are increasing. Harvest methods include selection, shelterwood, group selection, and clearcutting of stands smaller than 40 acres. Because aspen have soft, living bark they are easily wounded, predisposing them to various insects and diseases. Residual trees often are wounded during selection and shelterwood cuts. The importance of logging wounds on aspen, and subsequent attack by various insects and diseases, has not been extensively studied in forest situations.

Wounds on aspen trees often provide entrance points for canker and trunk rot fungi. Ceratocystis canker, caused by *Ceratocystis fimbriata* Ell. & Halst.; Cenangium canker, caused by *Cenangium singulare* (Rehm.) Davidson & Cash, and Cryptosphaeria canker, caused by *Cryptosphaeria populina* (Pers.) Sacc. usually begin in wounds. These cankers, along with Cytospora canker, caused by *Cytospora chrysosperma* Pers. ex Fr., are the major causes of tree mortality in Rocky Mountain aspen stands (Juzwik et al. 1978).

Heart rot is the primary cause of volume loss in aspen. Damage caused by heart rot results in cull of nonmerchantable stems. Hinds and Wengert (1977) found that decay losses in Colorado aspen were about 30% of the total gross board foot volume. Of the total cull volume, 66% was caused by trunk rots and 34% by butt rots. White trunk rot, caused by *Phellinus tremulae* Bond et Boris. (= *Fomes igniarius*), was the most frequently encountered decay. It was found in 5% of the 563 merchantable-sized trees in their study. Although trees are not directly killed by heart rot fungi, infected trees are frequently broken off during high winds.

The primary purpose of this continuing study is to determine the pathological effects of usual partial cutting practices in aspen stands. Other effects of partial cutting, including insect activity and sprout production, also were examined.

Methods

During 1974 and 1975, 11 plots were established in commercial aspen stands of northern New Mexico and southern Colorado. Plots were located in stands that had been partially cut within the previous three years. Cutting methods were those commonly used in commercial harvesting. The stands varied considerably in size; consequently the harvested plot size was varied to insure a representative sample of the area. Plots were square or rectangular and ranged in size from 0.6 to 1.2 acres. All trees 6 inches d.b.h. (diameter at breast height) or larger were examined in each plot. Trees were grouped in categories of live aspen, dead aspen, live conifer, or dead conifer. Each live aspen was numbered with paint for future identification.

A wide variety of site characteristics and stand conditions were represented by the plots (table 1). The original numbers of trees per acre and basal area prior to harvest was determined by adding the number of live and dead trees at the time of plot establishment to the number of stumps present on the plot and converting to a per acre basis. Basal area calculations were made by converting stump diameter to diameter at breast height using the relationship developed by Hann (1976).

In 1976, three uncut plots were established adjacent to the harvested plots as control plots for comparison of disease and mortality between cut and uncut stands. Because the control plots were near the extremity of the commercial stands, they were denser than the preharvest condition on the harvested plots, and contained, on the average, a larger basal area. Conse-

Table 1.—Individual aspen plot data

National Forest District Plot Number	Stand cut	Plot established	Plot size	Elevation	Aspect	Slope	Site index[1]	Average age
	year		acres	feet		percent		years
Carson National Forest								
Tres Piedras District								
Plot 1	1973	1974	0.6	9,650	east	10	67	70
Plot 2	1973	1974	0.8	9,600	east	10	67	70
Plot 3	1974	1974	0.9	9,650	west	30	72	80
Control Plot 3	—	1976	0.1	9,650	north	20	67	70
Taos District								
Plot 4	1973	1975	1.2	9,400	east	30	70	175
Plot 5	1973	1975	0.6	9,200	southwest	20	50	98
San Juan National Forest								
Pine District								
Plot 6	1973	1975	1.0	9,600	south	3	70	72
Plot 7	1974	1975	0.8	9,400	south	4	80	84
Plot 8	1972	1975	0.8	9,000	south	3	78	68
Plot 9	1972	1975	1.0	9,200	southwest	6	68	68
Control Plot 2	—	1976	0.2	9,000	south	3	78	68
Rio Grande National Forest								
Alamosa District								
Plot 10	1974	1975	1.0	10,100	southeast	5	58	86
Plot 11	1973	1975	0.6	10,200	southeast	0	60	87
Control Plot 1	—	1976	0.2	10,200	southeast	0	60	60

[1]*Base age = 80 years*

quently, a 0.1- or 0.2-acre size plot was used to include a number of trees comparable to the number on harvested plots.

Plot data for live aspen trees included: tree number; diameter; crown class; height of old wounds; height, size, and cause of recent wounds; whether wounds penetrated the cambium; whether wounds were infected with a disease; height, size, and species of cankers; height and species of conks or other rot indicators; and presence of wood borers. Data recorded for dead aspen and live or dead conifers included tree species, diameter, and cause of death, when known. Only standing dead trees or recently windthrown trees were tallied. The presence and condition of bark on dead trees were used for indicators as to whether they had died since harvesting. Stump diameter was recorded for all cut trees. Site index measurements were taken on six trees at each plot location. Mean site index (base age = 80 years) for each plot was calculated using the table developed by Jones (1966). Percent slope, aspect, elevation, and stand age were recorded for each plot.

A regeneration survey was made on each plot in 1977 and again in 1979 to determine the effect of basal area reduction on aspen sprout production. On harvested plots, the area was subdivided with a 1-chain grid. A milacre circular subplot (3.75-foot radius) was taken at the center of each 1-chain block (6-12 subplots per site). All trees on the milacre plot 6 inches d.b.h. or less were tallied. Similar subplots were established in the control plots, but a 0.5-chain grid was used (4-8 subplots per site).

Trees on cutover plots were examined at the time of plot establishment and again in 1977 and in 1979. Data were collected on the control plots at the time of establishment and in 1979.

Results and Discussion

Stand Conditions

Prior to harvest, plots averaged 255 trees per acre and a basal area of 157 square feet. Conifer species including white fir, *Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.; subalpine fir, *A. lasiocarpa* (Hook.) Nutt.; corkbark fir, *A. lasiocarpa* var. *arizonica* (Merr.) Lem.; Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco; Engelmann spruce, *Picea engelmannii* Párry ex Engelm., and ponderosa pine, *Pinus ponderosa* Dougl. ex Laws comprised 10% of the live stems at harvest time and 14% of the residual stems. Because of the small numbers of conifers encountered in this study, and since this study dealt with aspen, conifers were not considered in the calculations except in the regeneration subplots (table 2). Control plots were denser (380 trees per acre) than preharvest plots and had a slightly higher basal area (183 square feet per acre). There were no conifers on the control plots.

Harvesting removed 58% of the aspen larger than 6.0 inches d.b.h., or 69% of the basal area per acre. Residual basal area for live trees ranged from 26 (figs. 1 and 2) to 88 (figs. 3 and 4), with an average of 48 square feet per acre. Mean basal area on harvested plots dropped from 157 square feet before harvest to 47 in 1979, while basal area on the control plots increased from 183 to 190 square feet.

At the time of plot establishment, 969 live and 179 dead aspen were tallied on harvested plots (table 3). Dead trees accounted for 16% of the residual aspen. By reconstructing the harvested plots to preharvest condition, it was estimated that 7% of all aspen were dead, based on their appearance, at the time of logging. Assuming that no dead aspen were harvested, the 7%

Table 2.—Residual aspen basal area and regeneration on harvested and control plots

Plot Number	Residual BA-1979	Aspen-1977		Aspen-1979		Conifers-1979	
		< 1 inch d.b.h.	1-6 inch d.b.h.	< 1 inch d.b.h.	1-6 inch d.b.h.	< 1 inch d.b.h.	1-6 inch d.b.h.
	ft²/acre	*trees/acre*					
1	52	5,166 ± 2,449	166 ± 200	1,500 ± 764	167 ± 167	0	0
2	69	18,625 ± 7,549	375 ± 375	8,625 ± 2,645	750 ± 412	0	0
3	50	6,666 ± 2,014	0	5,222 ± 1,899	0	110 ± 111	0
4	39	4,000 ± 1,899	0	3,583 ± 1,422	333 ± 196	333 ± 196	0
5	85	500 ± 342	0	1,167 ± 833	0	0	0
6	39	11,500 ± 2,367	0	15,300 ± 4,773	100 ± 100	500 ± 342	100 ± 100
7	45	6,625 ± 1,821	125 ± 125	7,000 ± 2,061	1,250 ± 726	1,125 ± 398	750 ± 491
8	38	12,250 ± 4,447	0	13,625 ± 3,664	0	2,625 ± 1,700	0
9	51	9,833 ± 1,984	0	9,166 ± 1,598	0	250 ± 130	250 ± 130
10	34	47,900 ± 9,367	0	19,600 ± 4,206	300 ± 153	0	0
11	20	32,333 ± 9,888	0	18,000 ± 3,022	0	0	0
Mean	47	14,127 ± 4,203	60 ± 36	9,344 ± 1,950	264 ± 121	449 ± 241	100 ± 69
Control 1	209	3,333 ± 1,022	0	1,667 ± 498	0	0	0
Control 2	185	167 ± 167	0	0	0	167 ± 167	0
Control 3	177	500 ± 707	250 ± 354	167 ± 167	167 ± 167	0	0
Mean	190	1,333 ± 1,004	83 ± 83	611 ± 530	56 ± 56	56 ± 56	0

Table 3.—Aspen tree data for harvested and control plots in 1974-75 and 1979

Plot number	Year of plot establishment - 1974 or 1975						1979		
	Total	Cut	Dead	Live	Ave. d.b.h.	Wounded	Dead	Live	Ave. d.b.h.
	number trees				*inches*	*percent*	*number*		*inches*
1	141	68	4	69	9.7	69	15	54	10.2
2	257	122	21	114	9.8	59	21	93	10.6
3	205	80	37	88	9.1	72	5	83	9.7
4	80	20	10	50	14.8	62	14	36	15.3
5	159	64	16	79	11.0	89	5	74	11.3
6	278	147	14	117	7.3	76	10	107	8.2
7	204	98	18	88	8.3	73	8	80	9.1
8	223	140	12	71	8.2	87	5	66	9.1
9	410	234	31	145	7.6	86	6	139	8.1
10	312	202	6	104	7.2	71	3	101	7.8
11	223	169	10	44	8.0	98	15	29	8.6
Total	2,492	1,344	179	969	9.2	77	107	862	9.8
Control	**Year of plot establishment - 1976**						**1979**		
1	77	—	2	75	9.7	27	1	74	9.9
2	65	—	10	55	10.7	18	0	55	11.0
3	52	—	3	49	8.0	33	1	48	8.1
Total	194		15	179	9.5	26	2	177	9.7

mortality probably represented conditions in a natural stand before partial cutting. This closely coincides with the 8% mortality found in the control plots (fig. 4) which had 179 live and 15 dead trees at the time of establishment, and with the 9% mortality found in other natural aspen stands in Colorado (Hinds 1964).

Incidence of Wounds, Diseases, and Insects

The initial hypothesis was that partial cutting would result in numerous wounds on residual aspen, which would then increase the incidence of disease and subsequent tree mortality. At the time of plot establishment, 82% of the harvested plot trees sustained wounds: 5% with natural wounds, 14% with natural and logging wounds, and 63% with only logging wounds (table 3). Only 26% of the trees on control plots sustained wounds (i.e., excluding elk feeding wounds on aspen bark commonly referred to as elk barking), most of which were healed over. Wounds on control plot trees were caused by natural factors because the plots had not been logged. Elk barking was common on several plots. At the time of plot establishment, elk barking occurred on 16% of the trees in harvested plots and 53% of the control plot trees. One control plot had all of its trees barked by elk. During the period of observation, no elk barking wounds on any of the plots became visibly infected with a disease. In northwestern Wyoming, Krebill (1972) found that intensive elk barking increased aspen susceptibility to disease infection and subsequent mortality. In contrast, Hinds' (1964) study in Colorado showed no adverse effects from elk barking or rodent feeding. The reason for this disparity is unknown.

Figure 1.—Plot 11 had the lowest residual basal area of 26 square feet per acre (A), and six years after harvest there were 18,000 spouts per acre (B).

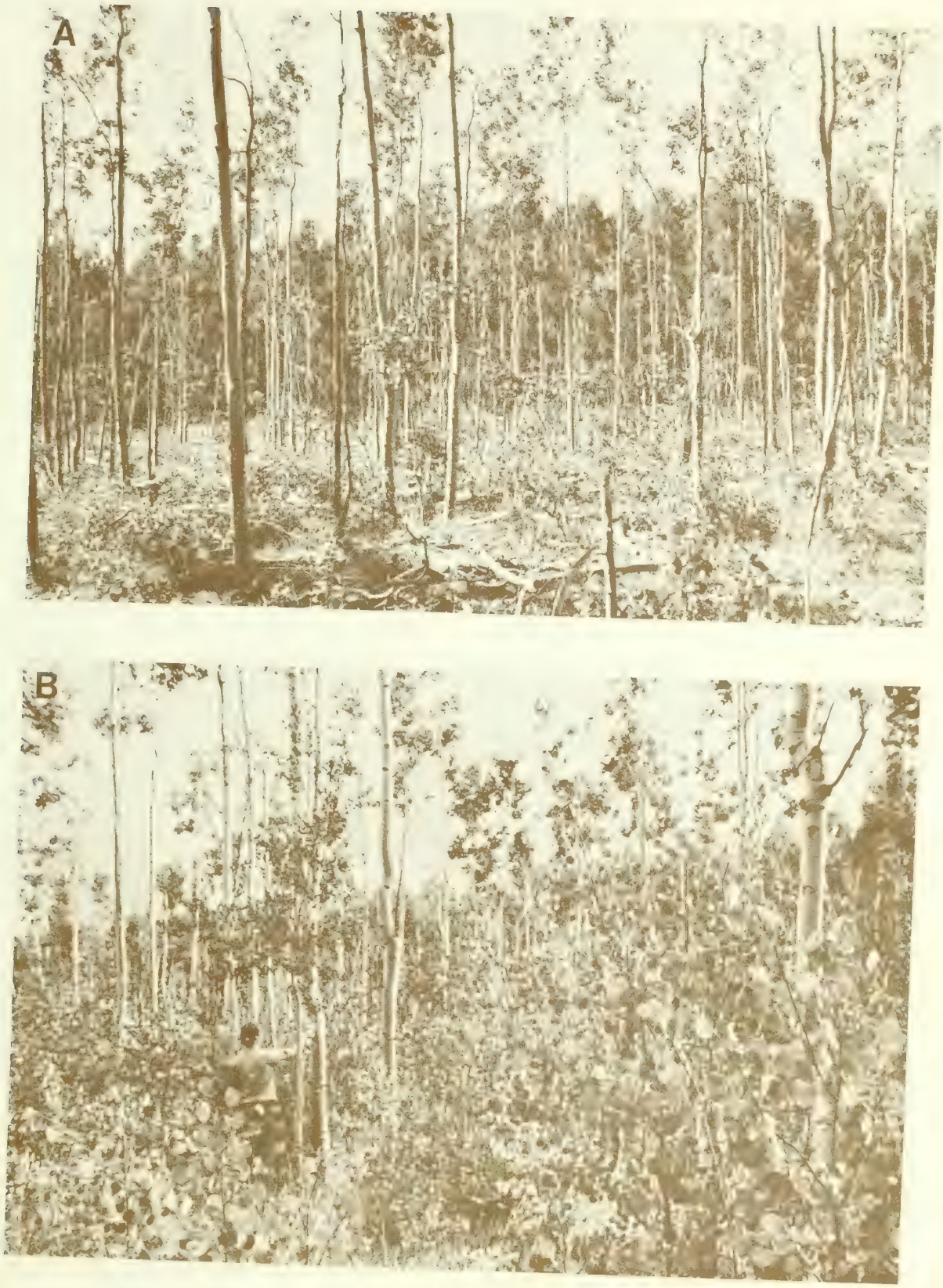

Figure 2.—A low residual basal area of 30 square feet per acre on plot 10 (A) resulted in 19,600 sprouts per acre five years after harvest (B).

Figure 3.—Even with a high residual basal area of 76 square feet per acre (A), plot 2 had 18,600 sprouts per acre four years after harvest (B).

Figure 4.—Stand conditions in control plot 1 were similar to those in harvested plots prior to harvest (A). Plot 5 had a high residual basal area (88 square feet per acre) and sprouts had been heavily grazed upon by cattle. Only 1,200 sprouts per acre were present six years after harvest (B).

In 1979, 89% of the 969 live residual trees on harvested plots were still living. The proportion of trees with visible cankers on these plots increased from 9% in 1974-75 to 45%, including canker caused mortality, by 1979. Live tree infection on the harvested plots by canker type in 1979 was: Ceratocystis (fig. 5A) 33%, Cenangium (fig. 5B) 4%, Cryptosphaeria (fig. 5C) 1%, Cytospora 2%, and unidentified cankers 6%. Trees often had more than one type of canker and some cankers could not be identified. Cankers were present on 7% of the live trees on control plots at the time of establishment and increased to 8% by 1979; all were Ceratocystis.

The association between natural or mechanical injuries to aspen bark and increased disease incidence has been previously documented. In a study of aspen mortality in Rocky Mountain campgrounds, Hinds (1976) found the incidence of cankers on live trees with numerous mechanical injuries to be: Ceratocystis—29%, Cytospora—10%, Cenangium—5%, and Cryptosphaeria—1%. In contrast, a recent survey (Juzwik et al. 1978) of natural aspen stands on nine National Forests in Colorado revealed the occurrence of cankers on live aspen to be: Ceratocystis—4.4%, Cenangium—1.1%, and Cryptosphaeria—1.1%. Canker incidence on the control plots in the present study was: Ceratocystis—8%, with no infections by Cenangium, Cryptosphaeria, or Cytospora.

White trunk rot, caused by the false tinder fungus, *P. tremulae*, was the primary rot found in the residual aspen. At the time of plot establishment, 7% of the residual trees on harvested plots had external signs (i.e., conks) of this fungus (fig. 6A) and fewer than 1% had other rots. By 1979, 11% of the trees had visible signs of white trunk rot and 4% were infected with other rot organisms. Three percent of the aspen on control plots were infected with white trunk rot in 1976, and none exhibited signs of any other rot. By 1979, 4% showed signs of white trunk rot, and 1% were infected with other rot organisms. In injured campground aspen, Hinds (1976) found white trunk rot conks on 6% of the trees. In western Colorado aspen stands, Hinds and Wengert (1977) encountered white trunk rot in 15% of the trees sampled, but conks were present only on 75% of the infected trees (i.e., 25% of the infected trees had no external signs of this fungus). In natural

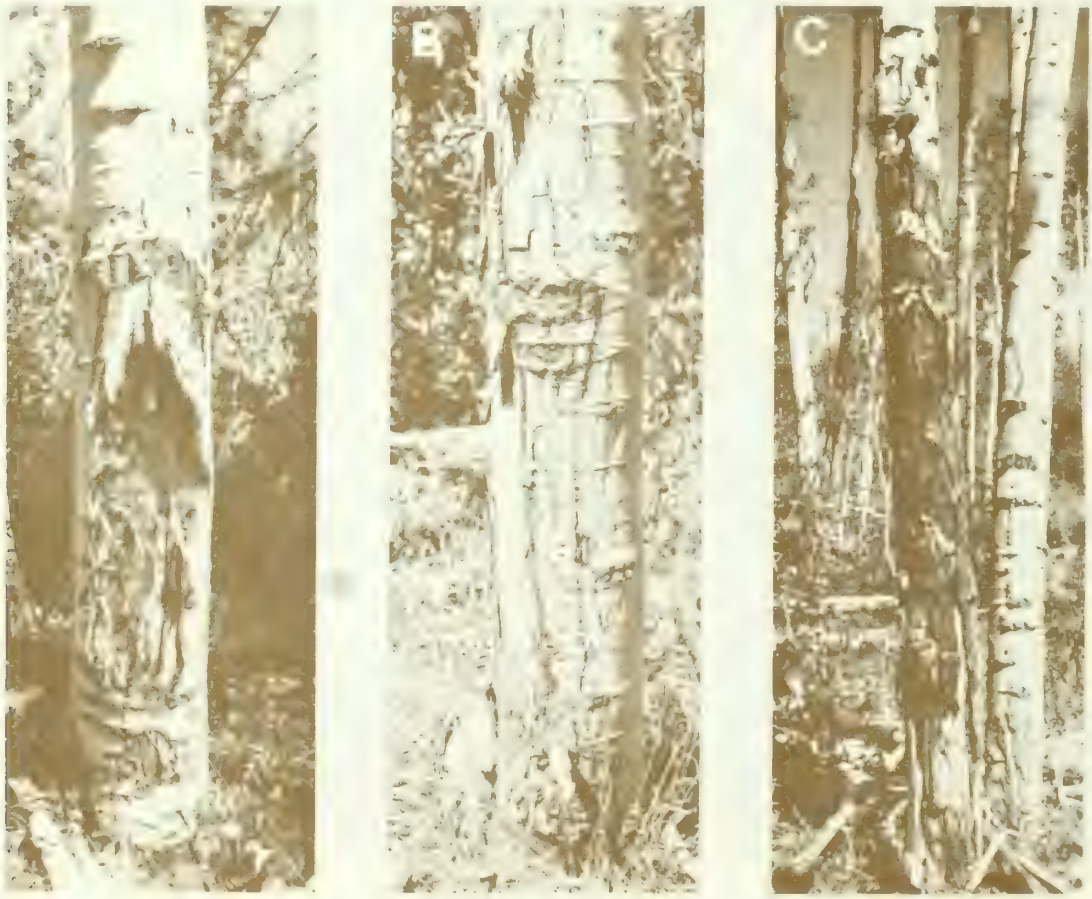

Figure 5.—Ceratocystis canker (A) was the most common disease found during the study, but Cryptosphaeria canker (B) and Cenangium canker (C) were the most important cankers causing tree mortality.

tands, Juzwik et al. (1978) found white trunk rot conks n 4% of the live aspen; however, Hinds (1964, unpub-shed data) found the conks on 6% of the live aspen xamined.

Long-term studies are needed to determine any rela-onships between rot incidence and wounds. Although ne percentage of trees showing signs or symptoms of ot increased on the harvested and control plots during ne relatively short time period of the observations in nis study, the slow development of conks precludes the stablishment of any definite relationship, at this time, etween wounding and trunk rot incidence. In addition, rees with conks on them probably would not have been ut during harvesting; thus, the percent of residual rees may have been artificially increased.

Sunscald often injures smooth-barked trees that are uddenly exposed to direct sunlight. Injury often ollows in stands opened by harvesting or thinning perations, and is most frequent on the south or outhwest sides of affected trees. Although areas of ark can be killed, trees seldom die from this injury lone. However, sunscald injuries often provide entry oints for disease organisms.

The incidence of sunscald on live aspen in this study uctuated during the period of observation. Initially, no residual trees on harvested plots were affected, but by 1977, about 7% (63 trees) of the living trees had been injured. Most injury occurred in plots 10 and 11 on the Rio Grande National Forest, Colorado. These plots had been heavily cut and retained the lowest residual basal areas of the 11 plots sampled. Both plots had a southeast aspect.

By 1979, many of the sunscald injuries had become infected with canker-causing fungi. Cankers that developed directly from sunscald wounds included 21 Ceratocystis cankers, six Cenangium cankers, three Cryptosphaeria cankers, and two Cytospora cankers. In addition, two trees were killed by sunscald alone. Five trees on plot 11 were cut between 1977 and 1979, but four of the five had severe sunscald in 1977 and probably died as a result of the injury. The trees were no doubt dead and cut as deadwood for firewood purpose. Of the remaining 24 trees (from the 63 affected in 1977), 19 had healed over and five still had sunscald damage in 1979. Although sunscald alone did not result in significant mortality, it predisposed half of the affected trees to infection by canker-causing fungi.

The occurrence of wood boring insects infesting aspen has been well documented (Hinds 1964, 1976; Hofer 1920; Juzwik et al. 1978; Krebill 1972), although

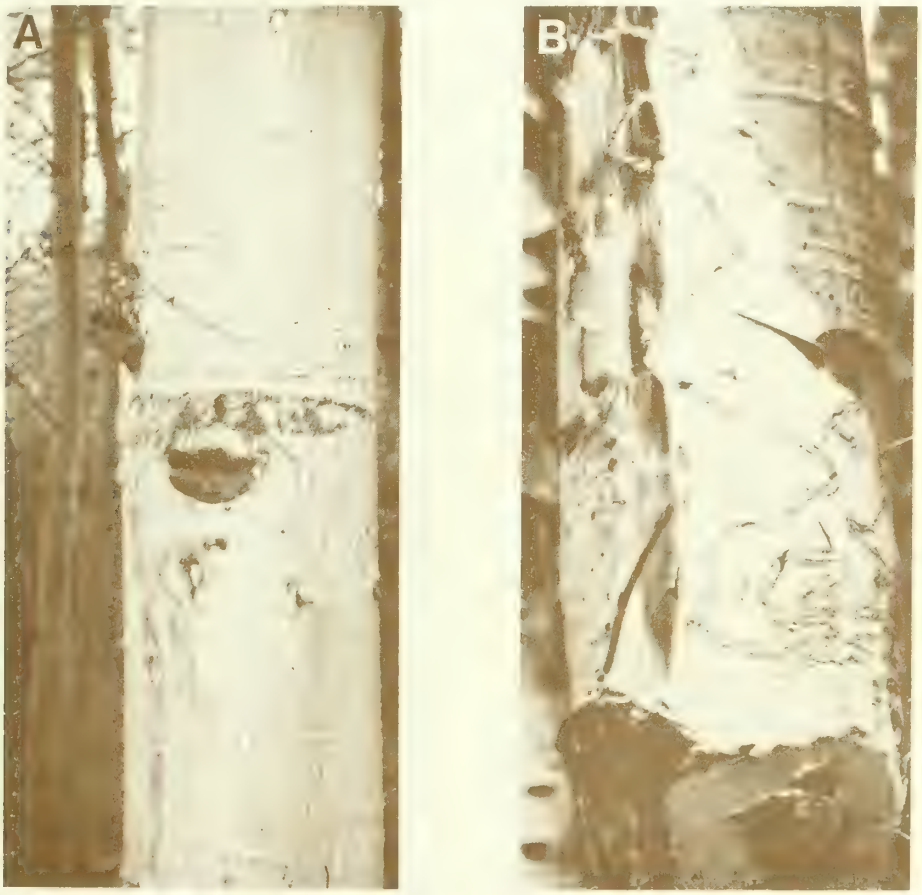

Figure 6.—Conks produced by the false tinder fungus *P. tremulae*, (A), were present on 11% of the trees in 1979. Removal of the outer bark on borer-infested trees revealed winding galleries (B), probably caused by the bronze poplar borer.

only one survey (Boss 1972) contained data on the insect species involved. Boss surveyed aspen insects in Colorado and found the bronze poplar borer, *Agrilus liragus* Barter and Brown, to be associated with natural and mechanically wounded aspen. Although no insects were collected in this evaluation, gallery patterns were similar to those caused by the bronze poplar borer (fig. 6B). Previous studies (Hinds 1964, Krebill 1972) indicated that borer attacks cause wounds in living aspen bark and predispose injured trees to other insects and diseases. The amount of tree mortality associated with borer attacks is unknown but assumed to vary with the insect species involved.

Previous surveys in Colorado indicated that the incidence of borers was about 2% or 3% in living trees in natural stands, and 18% in mechanically injured aspen (Hinds 1976). Eleven percent of the residual trees in harvested plots at the time of plot establishment were infested with borers. By 1977, the proportion increased to 13% and, in 1979, 30% of the live aspen were infested with borers. The infestation levels for control plots were 4%, 2%, and 12% in 1976, 1977, and 1979 respectively.

The cause of the substantial increase in the 1979 borer populations was not determined but it may be related to stand opening. The increase in attacks on control plots may be a result of borers spreading from the harvested areas into adjacent uncut areas. However, because no insect species were identified in this study, the overall importance of borer attacks could not be determined at this time.

Aspen Mortality

The major cause of tree mortality present on both harvested and control plots at the time of establishment was Cenangium canker. Mortality factors and the percentage of trees killed at that time were:

Harvested plots		Control plots	
Cenangium canker	47%	Unknown	53%
Logging damage	27%	Cenangium canker	40%
Unknown	17%	Butt rot*	7%
Windthrow	7%		
Cryptosphaeria canker	2%		

**Ganoderma applanatum* (Pers. ex Walls.) Pat. (= *Fomes applanatus*)

Residual aspen mortality varied from 3% to 34% of the trees per plot since plot establishment. Nine percent of all residual trees died between logging and plot establishment. An additional 11% of the residuals died between plot establishment and 1979. Thus, total tree mortality since logging was 20% of the residual live trees. Tree mortality on control plots between 1976 and 1979 was insignificant (1%). The difference between tree mortality on control plots and harvested plots corroborates the adverse effect of partial cutting in overall deterioration of the residual stand.

Tree mortality causes and their distribution among harvested plots since plot establishment were as follows:

Mortality factor	Percent of mortality	Percent of of plots
Canker:		
Cenangium	48	100
Cryptosphaeria	7	36
Ceratocystis	1	9
Cytospora	1	9
Windthrow	6	36
Wind breakage resulting from		
Cenangium canker	7	27
Ceratocystis canker	11	18
Trunk rot	9	55
Sunscald	3	18
Logging damage	2	9
Other	6	18

Ceratocystis canker alone was not a major cause of tree mortality (1%), but it predisposed some trees to wind breakage (11% of mortality). Wind breakage at Cenangium cankers was responsible for 7% of the tree mortality; however, the virulent nature of Cenangium canker probably negates the importance of wind as a contributing mortality factor. Wind, combined with trunk, butt, or root rots, was associated with 15% of tree mortality and may become more important in the future.

Canker-caused tree mortality will likewise add to future tree loss. Those trees with Cenangium and Cryptosphaeria canker will probably die within a few years, whereas the future of those with Cytospora and undetermined cankers are questionable at this time. In addition, the large number of residuals with Ceratocystis canker, in combination with wind breakage, may also add to future tree loss.

Regeneration Following Partial Cutting

Regeneration was sampled in 1977 and 1979. The mean number of sprouts smaller than 1 inch d.b.h. per acre decreased on harvested plots from 14,127 $\pm$ 4,203 in 1977 to 9,344 $\pm$ 1,950 in 1979 (table 3). The number of sprouts decreased on seven plots and increased on four. Sprouting was sparse to absent on the control plots. In most cases, the more trees harvested and/or the lower the residual basal area, the more sprouts that developed in the plot (figs. 1B, 2B, 3B). This result coincides with previous work (Schier and Smith 1979, Stoeckeler and Macon 1956), where number of sprouts increased with number of stems and basal area removed. Several harvested plots had some residual aspen trees in the 1- to 6-inch d.b.h. category, but these did not appear to affect sprout numbers. Conifers smaller than 6.1 inches d.b.h. were found on 6 of the 11 plots. By 1979, they represented 6% of the total regeneration, which was essentially the same proportion as before cutting.

Other studies (Baker 1925, Graham et al. 1963) have indicated that although partial cutting may maintain the aspen type, adequate sprouting requires nearly complete removal of the overstory. Most harvested plots had from 60% to 80% of the basal area removed during cutting. In a study of aspen regeneration on an Arizona clearcut, Jones (1975) found about 14,000 sprouts per acre the year after harvest. After four growing seasons, about 10,700 sprouts per acre remained on the clearcut. Other studies (Graham et al. 1963) indicated that a minimum of about 6,000 sprouts per acre were needed for adequate regeneration.

The mean number of sprouts per acre on harvested plots was similar to that reported by Jones (1975) even though these stands were partially cut. Most plots had the recommended minimum of about 6,000 sprouts per acre after harvest. By 1979, plots 1, 4, and 5 had substantially fewer sprouts than the remaining harvested plots. The decrease in live sprouts per acre on plot 1 was probably due to heavy cattle grazing following harvesting. The relatively low number of sprouts originating on plot 4 was probably a result of the advanced age of the parent stand. Aging aspen stands reportedly decrease in sprouting capacity (Maini 1972). Plot 5 (fig. 4B) had the highest residual basal area with only 41% of the preharvest basal area having been removed. Apparently, insufficient overstory removal resulted in a lack of root sprout stimulation.

The mortality rate for sprouts in plots 10 and 11 was typical for relatively high density suckering (Jones 1975). Competition and shading usually reduce sprout density to a level commensurate with site capability.

Summary

Each of the harvest methods used in Rocky Mountain aspen stands has its advantages and disadvantages. The purpose of this study was to determine the consequences of partial cutting in aspen stands. Our results suggest that partial cutting has several detrimental effects on residual aspen and may not be a desirable method of harvesting aspen stands.

Although there were differences between harvested and control plots in plot size and tree density, the increase in diseases and mortality is so great in the harvested plots that the question of comparability does not adversely affect the inferences obtained from the data. Sprouting was variable among subplots, which resulted in substantial standard errors; however, sufficient regeneration will be produced to maintain the stands as aspen.

Wounds on the living bark of aspen frequently predisposed affected trees to attack by insects and disease. Logging wounds often served as entry courts for canker-causing fungi. Partial cutting also exposed residual trees to increased sunlight and, in some cases, resulted in sunscald injuries. About half of the sunscald injuries became infected with canker diseases. In contrast, elk barking had no effect on insect or disease incidence.

In the 5-7 year period since logging, 45% of residuals alive after logging were infected with cankers and aspen mortality averaged 20%. This mortality rate was nearly three times that calculated for the plots before harvest, and 20 times the rate in control plots. The most important cause of tree mortality was Cenangium canker, followed by Ceratocystis canker in combination with wind. Cenangium cankers caused nearly half the tree mortality that occurred during the study. However, the current high incidence of Ceratocystis canker (33%) on residual trees may be of greater significance in the future.

Although land managers must consider many factors in determining the best method of harvesting a stand, results of this study indicate that the pathological problems associated with partial cutting aspen should be carefully considered.

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Acknowledgements

The authors express their appreciation to Robert L. James and Thomas D. Landis, formerly Forest Pest Management, State and Private Forestry, Lakewood, Colorado, for their assistance in plot establishment or data recording during the course of this study. Appreciation is also expressed to Forest Service personnel on the Carson, Rio Grande, and San Juan National Forests for their assistance in study plot locations.

Walters, James W., Thomas E. Hinds, David W. Johnson, and Jerome Beatty. 1982. Effects of partial cutting on diseases, mortality, and regeneration of Rocky Mountain aspen stands. USDA Forest Service Research Paper RM-240, 12 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Logging wounds on residual aspen, in partially cut stands, predisposed wounded trees to attack by insects and diseases. Five to 7 years after cutting, aspen mortality amounted to 20%; 41% of the live trees were infected with canker diseases; and 30% were infested with wood borers. Adequate sprouting occurred even though only 60–80% of the basal area was removed.

Keywords: cankers, decay, insects, *Populus tremuloides*, regeneration

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Research Paper RM-241

October 1982

Distribution of Western Spruce Budworm Egg Masses on White Fir and Douglas-fir

J. M. Schmid and P. A. Farrar
Rocky Mountain Forest and Range Experiment Station[1]

Abstract

Differences among trees and crown levels usually contributed significant variation to egg mass (EM) counts, while differences among aspects and between branches within the same crown level did not. When EM's per branch differed significantly among crown levels, branch size accounted for most of the difference. EM's per square meter of foliage of Douglas-fir were not generally significantly different among crown levels. EM's per square meter of foliage of white fir were significantly greater in the upper crowns than in the middle and lower crowns more than 50% of the time. The importance of each source of variation is discussed in relation to current EM-sampling techniques.

[1]*Headquarters is in Fort Collins, in cooperation with Colorado State University.*

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Management Implications

Sampling procedures currently used to predict defoliation from egg mass (EM) counts could be changed to increase precision. Differences among trees contribute a significant amount of variation to EM counts, so the number of sample trees should be as large as possible (see Discussion). Differences among crown levels also contribute significant variation, but the lower and middle levels are usually not different, so EM surveys can sample from either level. Differences among branches and aspects within the same crown level of a tree do not contribute significant variation, so only one branch need be removed from any side in the midcrown. If current sampling procedures are modified to use only one midcrown branch from six or more trees per cluster, the time spent sampling each tree will decrease, but sampling time for the cluster will increase. The cost of sampling each cluster may remain about the same or increase significantly, depending on how many additional trees are sampled, but the precision of the estimated EM density should also increase. Defoliation predictions for a mixed stand of Douglas-fir and white fir will overestimate the defoliation on white fir if defoliation is proportional to EM density, because densities are generally greater on Douglas-fir.

Introduction

Sampling methods for predicting defoliation by the western spruce budworm, *Choristoneura occidentalis* Freeman, exclusively use branch samples from Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco. This practice is quite valuable when comparing budworm densities on the same host in widely separated geographical areas, for example, Montana versus New Mexico. It has also allowed the establishment of standardized sampling so that Forest Service EM survey procedures are similar in the West.

Sampling one host is inadequate, however, when two or more hosts are mixed and a defoliation estimate for the other host is needed. Because major emphasis has been placed on Douglas-fir, little information has been developed on the distribution of budworms on other hosts. Thus, defoliation prediction techniques for Douglas-fir are questionable when used on other hosts, such as white fir, *Abies concolor* (Gord. and Glend.) Lindl.

This study was initially conducted to determine the EM distributions on white fir. Later, the study was expanded to examine EM distribution in mixed stands of white fir and Douglas-fir. More specifically, it sought to determine the distribution of EM's with respect to host species, trees, crown levels, and aspects.

Methods

EM-bearing branches were collected from three crown levels on host species from locations specified in table 1. The locations were selected because they had easily accessible trees with abundant budworm populations and because they were in different geographic areas. Collection areas were about 1 ha in size, except for the Los Alamos location, which was several hectares.

Whole branches were pruned from trees in 1977 and 1978. However, whole branches from the middle and lower crowns of white fir and, occasionally, Douglas-fir exhibited dichotomy and were really composed of two or more branchlets. These branchlets often lacked live needles at their connecting base, so they were considered separate branches. Furthermore, because whole branch examination was impractical for the data it yielded, branchlets were removed from the middle and lower crowns in 1979 and 1980. Whole branches were still removed from the upper crowns in these years. The branches were put in sacks and transported to cold storage units in Fort Collins.

In 1977, each branch was cut into 15-cm-long segments beginning at the tip and working toward the base of the branch along the primary stem. New EM's per segment were recorded and numbers per branch were compared using analysis of variance, testing for significant variation among trees, crown levels, aspects, and branches, $P = 0.05$. Numbers per respective 15-cm segment were used in two ways: (1) to compute mean percent of EM's for 1- to 15-cm, 15- to 30-cm, 30- to 45-cm, and >45-cm branch segments and (2) to compute the mean number in cumulative (0- to 15-cm, 0- to 30-cm, 0- to 45-cm) branch segments.

In 1978, each branch was measured metrically for length and width and assigned a form, either triangular or rectangular, whichever best approximated its shape, in order to later determine branch area. The branches were then examined for EM's in two ways: (1) half of the branches (one branch from each aspect/crown-level combination) were inspected in 14-cm-long segments be-

Table 1.—Sampling information regarding collection of EM-bearing branches

Year	Collection location near	Host species	Number of trees	Number crown levels	Aspects	Branches per crown level	Collection dates
1977	La Veta and Rye, Colo.	White fir	20	3	2	4 (2N, 2S)	September 13, 1977
1978	Los Alamos, N. Mex.	White fir	25	3	2	4 (2N, 2S)	July 24 - August 3, 1978
	Taos, N. Mex.	White fir	25	3	2	4 (2N, 2S)	July 24 - August 3, 1798
	Vallecito Reservoir, Colorado	White fir	25	3	2	4 (2N, 2S)	July 24 - August 3, 1978
	La Veta Pass, Colorado	White fir	25	3	2	4 (2N, 2S)	July 24 - Augsut 3, 1978
1979	Los Alamos, N. Mex.	White fir	25	3	—	1	July 31 - August 2, 1979
		Douglas-fir	24	3	—	1	July 31 - August 2, 1979
	Vallecito Reservoir, Colorado	White fir	17	3	—	1	September 26-27, 1979
		Douglas-fir	17	3	—	1	September 26-27, 1979
1980	Los Alamos, N. Mex.	White fir	10	3	—	1	August 5-7, 1980
		Douglas-fir	10	3	—	1	August 5-7, 1980
	Taos, N. Mex.	White fir	10	1	—	1	August 5-7, 1980
		Douglas-fir	10	1	—	1	August 5-7, 1980
	Vallecito Reservoir, Colorado	White fir	10	3	—	1	August 13-14, 1980
		Douglas-fir	10	3	—	1	August 13-14, 1980
	La Veta Pass, Colorado	White fir	10	3	—	1	August 21, 1980
		Douglas-fir	10	3	—	1	August 21, 1980

[1]*After 1978, aspects were disregarded and branches taken from any side of the tree.*

ginning at the tip or where live foliage began and working toward the base of the branch and (2) the other half of the branches were examined in 14-cm-wide concentric bands which began on the outer edges of the foliage and progressed inwardly. EM's were removed, classified as new or old, and the number of new EM's recorded with the branch measurements. After examination, the foliage was stripped from the stems and sacked in paper bags. The foliage was later dried for 24 hours at 100° C to obtain its oven-dry weight. Branch examination was unexpectedly slow because foliage removal was slower than expected. Some branches then deteriorated in cold storage when, because of the delay, mold frequently developed or the needles dehydrated, dropping from the stems. Deterioration prevented examination of all branches from each location. The data were thus only partially complete. Where possible, EM's per branch, per square meter, and per 100 g of foliage were analyzed for differences among trees and crown levels but not aspects or branches.

In 1979, and 1978 study was repeated, except that only one branch was removed per crown level, Douglas-fir branches were collected simultaneously, and the branches were only examined in 14-cm units beginning at the tip and working toward the base.

The EM information was assembled into three categories: (1) new EM's per branch, (2) new EM's per square meter of foliage, and (3) new EM's per 100 g of foliage. Each category was analyzed in a three-way analysis of variance testing for significant variation associated with host species, trees, and crown levels, $P = 0.05$. If significant interaction existed between hosts and crown levels, a one-way analysis of variance was executed for each host to affirm or deny significant differences in crown levels.

The 1980 branches were collected and examined as in 1979, except that the foliage was not dried and weighed. The number of new EM's per branch and per square meter of foliage were analyzed using analysis of variance testing for significant differences among host species, trees, and crown levels, $P = 0.05$. When crown-level variation appeared inconsistent between hosts, a separate one-way analysis was used to test for significant differences among crown levels for each host. Using the number of EM's in each 14-cm segment, the percentage of EM's in segment 1, segments 1 and 2, segments 1, 2, and 3, and so forth, were determined.

Results

Sources of Variation in Egg Mass Counts

EM's per branch varied significantly among trees and crown levels in 1977 (table 2). Aspects, branches, and aspect/crown-level interaction contributed insignificant variation. Crown levels contributed the most variation, at least three times the amount contributed by trees.

Data from 1978 were insufficient to determine the significance of each source of variation. Nevertheless, by inspection, trees and crown levels appeared important, while aspects appeared unimportant, as demonstrated in the 1977 data.

In 1979, the amount of variation contributed by each factor varied among locations and among the basis for comparison (branch, branch area, or branch weight).

Host species contributed significant and greater amounts of variation in all three analyses (EM's per branch, per square meter, and per 100 g) of the Vallecito Reservoir data, while host species at Los Alamos contributed less variation than crown levels in all three analyses and significantly in only the analysis of EM's per 100 g. Crown levels contributed significant variation in the EM's per square meter and per 100 g analyses for both locations but insignificant variation in the analyses of EM's per branch of the Vallecito Reservoir data (table 2). Host species and crown level interacted significantly in the analyses of EM's per branch and EM's per square meter for the Vallecito Reservoir data and was nearly significant in the analysis of EM's per 100 g of the Los Alamos data. The interaction was usually significant when the variation associated with hosts was different. Trees contributed significant variation in the analysis of EM's per branch for both locations and for the analyses of EM's per square meter and EM's per 100 g of the Los Alamos data.

In 1980, host species contributed significant variation in EM counts at Los Alamos and La Veta Pass for both types of analyses (table 2), Douglas-fir having significantly higher counts than white fir. Variation contributed by crown levels was only significant at Vallecito Reservoir and La Veta Pass for the analysis of EM's per branch, although crown-level differences within each species at La Veta Pass were not significantly different. Interactions between host species and crown levels were never significant. Trees contributed significant variation in the analyses of EM's per branch for three of four locations but contributed significant variation for only Vallecito Reservoir in the analyses of EM's per square meter.

Mean Number of Egg Masses per Branch, per Square Meter of Foliage, and per 100 g of Foliage

In 1977, EM's per midcrown branch were significantly greater than on lower crown branches (table 3). EM's per branch, per square meter, and per 100 g of foliage were highest in the upper crown in 1978 (table 3).

EM counts for Douglas-fir and white fir in 1979 exhibited similar relationships for the two locations (table 3). On a per branch basis, EM's on Douglas-fir were greatest in the middle crown (40 at Los Alamos and 21 at Vallecito Reservoir) and significantly lower in the upper crown (22 and 11 for the two respective locations), while counts on white fir were not different among crown levels. EM's per square meter of foliage on Douglas-fir were not different among crown levels while upper crown means of 96 and 36 on white fir were significantly greater than respective middle (51, 21) and lower (41, 12) crown means. EM's per 100 g of foliage followed the same relationships for each host as EM's per square meter—no difference among crown levels for Douglas-fir and greater numbers in the upper crown for white fir. EM densities on Douglas-fir were the same or higher than on white fir (table 3). Densities in the upper crown were similar for the two species while Douglas-fir had greater densities in the lower and middle crowns.

In 1980, mean numbers of EM's per branch were insignificantly highest in midcrown on both hosts (table 3). Mean numbers per square meter were highest in the upper crown of both hosts at Los Alamos but varied between upper and middle crown by host at Vallecito Reservoir and La Veta Pass. Densities were generally greater on Douglas-fir than on white fir.

Table 2.—Sources of variation in EM counts[1]

Variable Source of variation	1977 San Isabel National Forest, Colorado	1979 Vallecito Reservoir, Colorado	1979 Los Alamos, N. Mex.	1980 Los Alamos, N. Mex.	1980 Taos, N. Mex.	1980 Vallecito Reservoir, Colorado	1980 La Veta Pass, Colorado
EM's per branch							
Host species (HS)	—	S	NS	S	NS	NS	S
Trees	S	S	S	S	NS	S	S
Crown levels (CL)	S	NS	S	NS		S	S
Aspects (A)	NS	—	—	—	—	—	—
Branches	NS	—	—	—	—	—	—
CL x A	NS	—	—	—	—	—	—
HS x CL	—	S	S	NS		S	NS
EM's per square meter of foliage							
Host species (HS)	No data	S	NS	S	NS	NS	S
Trees		NS	S	NS	NS	S	NS
Crown levels (CL)		S	S	NS		NS	NS
HS x CL		S	NS	NS		NS	NS
EM's per 100 g of foliage							
Host species (HS)	No data	S	S	No data	No data	No data	No data
Trees		NS	S				
Crown levels (CL)		S	S				
HS x CL		NS	S				

[1] *S = significant at the 0.05 level*
NS = nonsignificant
— = not able to determine because of sampling design

Table 3.—Mean number of new EM
oven-dry weight of foliage for Do

Variable Crown level	1977 San Isabel National Forest, Colorado	1978 Los Alamos, N. Mex.	1979 Los Alamos, N. Mex.		1979 Vallecito Reservoir, Colorado	
	White fir	White fir	Douglas-fir	White fir	Douglas-fir	White fir
EM's per branch						
Upper	5ab ± 7	9a ± 9	22a ± 11	34a ± 22	11a ± 10	14a ± 12
Middle	8a ± 8	5ab ± 7	40b ± 27	35a ± 23	21b ± 12	10a ± 6
Lower	3b ± 3	3b ± 4	32ab ± 24	26a ± 26	17ab ± 14	7a ± 6
EM's per square meter of foliage						
Upper	No data	22a ± 19	84a ± 50	96a ± 60	38a ± 22	36a ± 24
Middle		11b ± 13	74a ± 56	51b ± 32	55a ± 31	21b ± 11
Lower		11b ± 13	59a ± 51	41b ± 69	35a ± 26	12b ± 9
EM's per 100 g of foliage						
Upper	No data	5a ± 4	15a ± 7	17a ± 10	9a ± 4	7a ± 4
Middle		3b ± 3	14a ± 6	10b ± 5	9a ± 4	6ab ± 3
Lower		3b ± 3	12a ± 7	8b ± 5	7a ± 4	4b ± 2

'Means within a set of crown levels for a particular host which are followed by the same letter are not significantly different according to Tukey's multiple comparison procedure, P = 0.05.

Within-branch Distribution of Egg Masses

The percent of new EM's per 15-cm branch segments of white fir in 1977 followed the same pattern in the crown levels of the north and south sides except for the lower south level (table 4). Percentages of EM's in the first 30 cm ranged from 9% to 25% of the total EM's per branch.

Percent of new EM's on cumulative 14-cm units was generally slightly higher for respective segments from a middle crown branch of white fir than for Douglas-fir in 1979 (table 5). White fir had 9% of the total EM's in the first 28 cm, while Douglas-fir had 6% (table 5). For the first 70 cm (5 14-cm units), white fir had 33-41% of the total EM's, Douglas-fir had 28-29%.

In 1980, the percentage of new EM's in the 14- and 28-cm segments was slightly greater than for each host in 1979. However, the 1980 percentages for the 70-cm length were 5-20% greater than for the respective hosts in 1979 (table 5).

Table 4.—Distribution of new EM's on cumulative 15-cm branch segments of white fir, 1977

Aspect Crown level	Cumulative branch segments			
	0-15 cm	0-30 cm	0-45 cm	> 45 cm
	cumulative percent			
North				
Upper	4	13	37	100
Middle	2	15	40	100
Lower	2	16	38	100
South				
Upper	3	9	28	100
Middle	6	14	25	100
Lower	15	25	46	100

Discussion

Egg Mass Variation—Sampling Relationships

The significant variation contributed by trees and crown levels and the insignificant variation contributed by branches and aspects agree with the results of Morris (1955) for balsam fir, *Abies balsamea* (L.) Mill. and of Harris and Edwards (1960) for subalpine fir, *Abies lasiocarpa* (Hook.) Nutt. Variation among crown levels in this study was generally larger than among trees, just the opposite of Morris's results. Carolin and Coulter (1972) also found occasional significant differences in crown levels of Douglas-fir, especially when EM's were expressed on a per branch basis rather than per 1,000 square inches. In later studies of grand fir, *Abies grandis* (Dougl. ex D. Don) Lindl., Carolin and Coulter (1975) found significant differences in EM's per 1,000 square inches among crown levels. The insignificant variation associated with branches (within tree) differs from the results of Carolin and Coulter (1959),[2] who found significant within-tree variation in the same crown level.

Each significant source of variation relates to the current EM survey procedure. In recent years, the EM counts from annual surveys have explained between 22% and 65% of the subsequent defoliation in three Forest Service Regions in the West (USDA Forest Service 1978). Many factors contribute to these low correlations, some of which can be attributed to the significant sources of variation.

[2]*Carolin, V. M., and W. K. Coulter (1959). Research findings relative to the biological evaluation of spruce budworm infestations in Oregon. Preliminary draft to aid in discussion at Western Forest Insect Work Conference, Ogden, Utah, March 1960. Draft on file at Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.*

meter of foliage, and per 100 g of
77–1980

	1980 Taos, N. Mex.		1980 Vallecito Reservoir, Colorado		1980 La Veta Pass, Colorado	
	Douglas-fir	White fir	Douglas-fir	White fir	Douglas-fir	White fir
S.D.[1]						
7			18a ± 12	11a ± 6	5a ± 4	2a ± 2
8	34 ± 15	24 ± 20	20a ± 14	28b ± 16	11a ± 8	5a ± 4
5			19a ± 18	13a ± 7	11a ± 9	4a ± 3
1			84a ± 79	52a ± 24	10a ± 8	4a ± 4
8	79 ± 27	58 ± 39	53a ± 32	65a ± 30	12a ± 8	7a ± 3
0			55b ± 50	52a ± 29	13a ± 7	7a ± 10
	No data	No data	No data	No data	No data	No data

The current EM survey procedure is to remove two midcrown branches from each of three trees in a cluster, with the clusters scattered but established in specific locations throughout the entomological unit. This procedure supplanted that of McKnight et al. 1970) on National Forests because of a desire to obtain annual information on population trends in addition to defoliation predictions. The 3-tree-cluster procedure evolved from two sources: (1) the outstanding work of Morris (1955), who used cluster sampling for population dynamics work in 25-acre stands in New Brunswick and (2) an unpublished study in the Pacific Northwest Region, USDA Forest Service, which showed through multistage analyses of larval counts in opening buds, the 3-tree, 2-branch sample to be the most precise for the allocation of the resources (Twardus 1980 personal communication). Although three trees, instead of the one tree used by McKnight et al. (1970), should improve the precision, the poor to fair correlations of defoliation with EM counts suggests additional improvements need to be made if the procedure is used in the future.

Some inadequate correlations may result from too few clusters being sampled in the entomological unit. McKnight et al. (1970) recommended at least 25 1-tree plots be sampled. Sampling 9 3-tree plots would provide the branch equivalent to 25 1-tree plots, but the lesser number of plots may not encompass the variation within the unit. If the three trees in a cluster are fairly homogeneous, then the three trees essentially represent the equivalent of one tree, and 25 or more

Table 5.—Distribution of new EM's on cumulative 14-cm segments of midcrown branches of Douglas-fir and white fir

Location Date, Host	Distance from tip (cm)					
	≤14	≤28	≤42	≤56	≤70	≤84
	cumulative percent					
Los Alamos, N. Mex.						
1979, Douglas-fir	2	6	13	20	28	39
White fir	2	9	19	28	41	52
1980, Douglas-fir	2	9	15	25	37	49
White fir	3	11	31	39	54	61
Taos, N. Mex.						
1980, Douglas-fir	1	11	25	36	46	47
White fir	2	9	20	37	45	62
Vallecito Reservoir, Colorado						
1979, Douglas-fir	2	5	12	19	29	36
White fir	2	7	14	25	33	46
1980, Douglas-fir	5	10	15	20	34	45
White fir	3	11	24	35	53	66

clusters may have to be taken to obtain the equivalent of the 25 1-tree plots of McKnight et al. (1970).

Another factor contributing to low correlations may be the number of trees in the cluster. While the data from this study do not allow evaluation of among-tree variation to cluster sampling, the fact that trees contribute significant variation suggests that the most appropriate number of trees per cluster and the number of clusters per unit need to be determined.

Sampling two branches per tree is unwarranted because the results of Morris (1955), Harris and Edwards (1960), and this study, all indicate branches from the same crown level do not contribute significant variation. Morris (1955) mentions two other pertinent considerations: (1) "The use of a smaller sample unit such as one branch per tree is to be recommended for less exacting purposes such as insect survey" and (2) "There is little advantage in drawing more than one sample unit per tree, unless the time acquired to move from tree to tree is very high in relation to the time required to draw and examine one sample unit." Stands in southern Colorado/northern New Mexico are more open-grown with greater distances between trees than in balsam fir stands in New Brunswick, so maneuverability is enhanced and costs for sampling one branch from six trees would not be substantially different than sampling two branches from three trees. Thus, the precision of the estimate could be increased by taking one branch from each of a greater number of trees.

Crown-level differences will not affect the accuracy of the defoliation estimate if samples are drawn from the lower and middle crowns. Because middle and lower crown EM densities were not generally significantly different (table 3), either level can be sampled. Sparsely foliated branches from the extreme lower crown should be avoided, but, otherwise, any branch from the lower and middle crowns could be selected.

Another factor affecting the correlation between EM counts and defoliation may be the within-branch distribution of EM's. Carolin and Coulter (1959) found 34-59% of the EM's on 15-inch (38-cm) samples from five locations over a 3-year period. The mean percentage of new EM's per 70-cm sample from Douglas-fir ranged from 28% to 46% (table 5), and variation around the means was large. If a mean value for the 70-cm sample remained within this range throughout the life of an infestation, then better correlation between EM counts and defoliation might be expected. However, changes in this percentage as defoliation varies could partially explain the lack of good correlation between EM counts and defoliation (see Grimble and Young 1977).

The importance of stand density, stand composition, and site on variation in EM densities remains relatively undetermined. Williams et al. (1971) determined larval densities to be related to basal area and tree species, so these factors may contribute significantly to EM densities. If stand characteristsics are a factor, different numbers of trees may have to be sampled in the various stands to acquire the same relative precision. In current EM surveys, a mixture of 3-tree cluster plots from dense and open stands may be creating some imprecision and causing poorer correlation between EM densities and subsequent defoliation.

The margin of error for estimates of EM density has been of little concern in past surveys. Based on data from this study, densities with an error margin of 10% of the mean would require samples from more than 75 trees per area. This intensity may be prohibitive for budworm surveys so a less precise estimate must be accepted. Assuming each tree from this study represents a homogeneous cluster, then estimates of EM density with an error margin of 20% with a 95% probability could be achieved by sampling 20 to 30 clusters in most cases. Future work should investigate which combination of clusters, trees per cluster, and branches per tree yield the most precise and cost-effective estimate.

Host Species and Defoliation Prediction

The relationship between EM densities on Douglas-fir and other hosts is important because defoliation prediction techniques are currently available for only Douglas-fir. If defoliation on other hosts would be the same or less than on Douglas-fir, then the current prediction plan could be used in a mixed stand of hosts. Optimism must be guarded in this case because Carolin and Coulter (1975) found greater bud-killing on grand fir than on Douglas-fir even though EM denisities were similar for the two hosts. In this study, if defoliation was proportional to EM per square meter for Douglas-fir and white fir, then defoliation should be similar in the upper crowns of both species in 1980 and greater on Douglas-fir in 1981. Defoliation in the lower and middle crowns of Douglas-fir should be greater in both years than on white fir. If defoliation for the stand is based on Douglas-fir defoliation, then it would be overestimated because white fir would suffer less damage below the upper crown. In contrast, larval densities in 1979 were higher on white fir than on Douglas-fir, so that if the EM relationship between white fir and Douglas-fir was similar to that of 1979 and 1980, the greater larval survival on white fir may compensate for the lesser EM densities and result in an underestimate of white fir defoliation.

Factors Causing Significant Differences in Egg Mass Densities

Significant differences in EM's per branch result from significantly different branch sizes. Schmid and Morton (1981) found upper crown branches of Douglas-fir and white fir had significantly less area than middle crown branches. Even though eggs may be deposited in greater densities on upper crown branches (see square meter data, table 3), the smaller size of these branches causes the total numbers of EM's to be considerably less than on middle crown branches.

The generally insignificant differences in EM densities per square meter or per 100 g of foliage among

rown levels of Douglas-fir is not readily explainable. ignificant interaction between crown levels and trees nay have masked crown-level differences. Female noths may oviposit equally on all suitable branches in he crown levels of Douglas-fir, although this seems unikely because they appear to oviposit a greater density f EM's in the upper crowns of white fir.

New EM's in different crown levels of white fir were ignificantly different per branch at only Vallecito Resrvoir in 1980. They were significantly different per quare meter at Los Alamos in 1979 and 1980 and at 'allecito Reservoir in 1979 (table 3) where the upper rown level density was significantly greater than the ower crown level and midcrown densities were usully intermediate to the upper and lower crown values. 'emale moths apparently oviposit a higher density of EM's in the upper crowns of white fir.

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Acknowledgments

Work leading to this publication was funded by the Canada/United States Spruce Budworms Program, an accelerated research, development, and applications program sponsored by the USDA Forest Service.

Special thanks are due Douglas Parker, Eugene Lessard, Iral Ragenovich, and their summer crews, Forest Pest Management, Southwestern Region, USDA Forest Service, who collected egg-mass-bearing branches in the Los Alamos area.

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Schmid, J. M., and P. A. Farrar. 1982. Distribution of western spruce budworm egg masses on white fir and Douglas-fir. USDA Forest Service Research Paper RM-241. 7 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Host species, trees, and crown levels usually contributed significant variation to egg mass counts, while aspects and branches within a crown level within a tree did not. This information is discussed in relation to sampling.

Keywords: Western spruce budworm, *Choristoneura occidentalis*

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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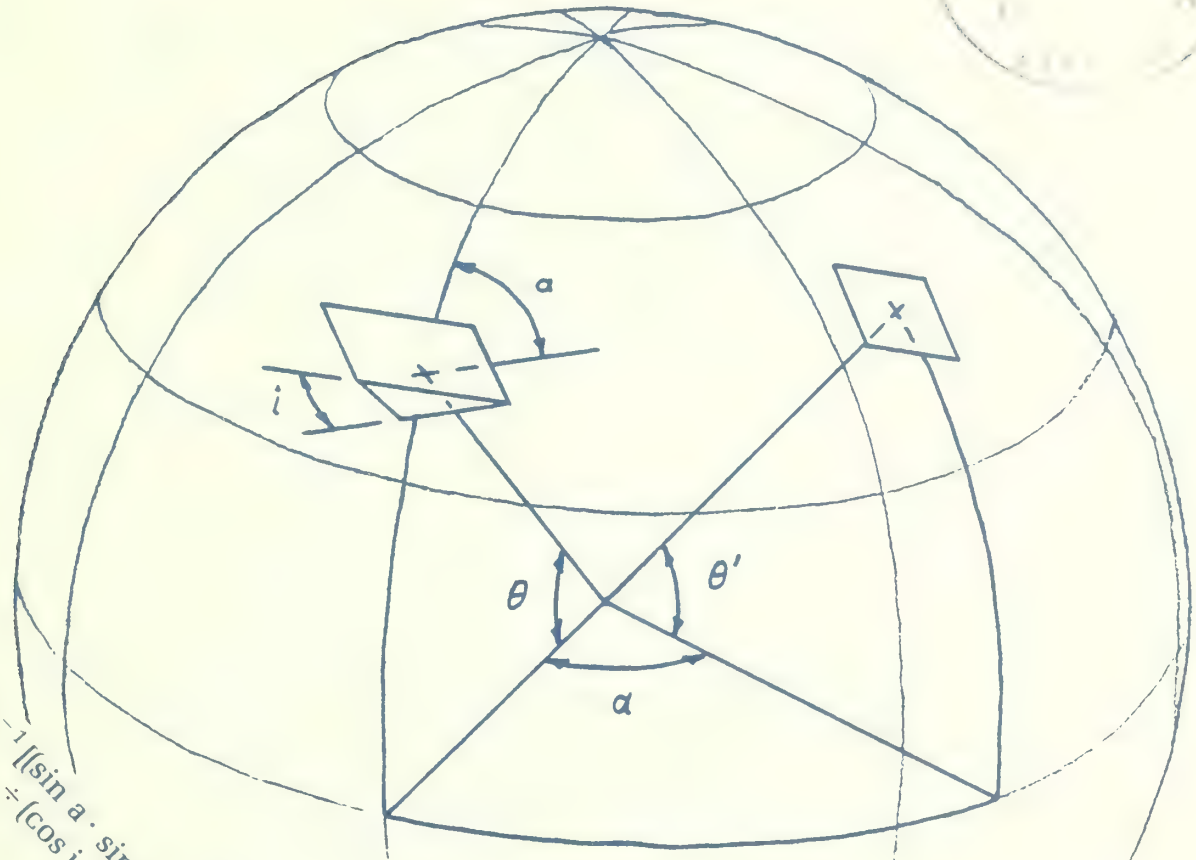
Determination of Potential Direct Beam Solar Irradiance

Merrill R. Kaufmann and James D. Weatherred



$$\alpha = \tan^{-1}[(\sin a \cdot \sin i) \div (\cos i \cdot \cos\theta - \cos a \cdot \sin i \cdot \sin\theta)]$$

$$\theta' = \sin^{-1}(\sin i \cdot \cos a \cdot \cos\theta + \cos i \cdot \sin\theta)$$

$$M_i = \frac{M_o}{r^2}[\sin\theta' \cdot \sin\delta + \cos\theta' \cdot \cos\delta \cdot \cos(\omega t'')]$$

Research Paper RM-242
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

Abstract

Procedures are presented for calculating potential direct beam solar irradiance, corrected for latitude, azimuth and inclination of slope, date, and time of day. Equations are structured to permit the user to calculate instantaneous or total daily irradiance using total incoming shortwave irradiance or any selected portion of the solar spectrum.

Kaufmann, Merrill R., and James D. Weatherred. 1982. Determination of potential direct beam solar irradiance. USDA Forest Service Research Paper RM-242, 23 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

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Keywords: Solar irradiance, direct beam irradiance, latitude, declination, azimuth, inclination

USDA Forest Service
Research Paper RM-242

October 1982

Determination of Potential Direct Beam Solar Irradiance

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Determination of Potential Direct Beam Solar Irradiance

Merrill R. Kaufmann and James D. Weatherred

Introduction

Potential direct beam solar irradiance is the radiation received above the earth's atmosphere. The maximum direct beam irradiance is received when a surface above the atmosphere is perpendicular to the sun's rays. For incoming shortwave irradiance, this is equivalent to the solar constant, generally taken to be 1360 $W \cdot m^{-2}$ (1.95 $cal \cdot cm^{-2} \cdot min^{-1}$).

Actual irradiance received at the earth's surface is lower than the potential direct beam irradiance. The reduction results from a number of factors, some of which are highly predictable because they are geometric in nature, and some of which are less predictable because of varying atmospheric effects.

Geometric effects include latitude, solar declination, distance between the sun and earth (radius vector), inclination and aspect of the plane in question, time of day, and obstructions. The plane or surface may be a hillside, leaf, wall or roof of a building, solar collector, etc. Atmospheric effects include depth of clear atmosphere through which radiation must pass (a function of solar declination, latitude, elevation, and time of day), radiation scattering (a function of atmospheric composition and contamination), and cloudiness (Gates 1980).

While knowledge of the actual irradiance received at a surface is useful to hydrologists, plant physiologists, solar energy engineers, and others, the complexities of predicting actual irradiance are great because atmospheric conditions are dynamic. Knowledge of potential direct beam irradiance is useful because potential irradiance is a maximum limit for actual irradiance and is usually used to derive estimates of actual irradiance.

Incoming shortwave irradiance is of interest to hydrologists, micrometeorologists, and solar engineers because of its direct role in determining the energy balance of a given site. In some cases, however, only a portion of the solar spectrum is of concern. For example, a plant physiologist studying photosynthesis or stomatal behavior may be concerned only with photosynthetic photon flux density (visible irradiance, 400 to 700 nm), while a human pathologist evaluating skin disorders may be interested in the ultraviolet portion of the spectrum.

Frank and Lee (1966) provided tables giving the times of sunrise and sunset and the total daily incoming irradiance, which covered a range of latitudes, aspects, slopes, and times of year. Buffo et al. (1972) also provided extensive tables and figures of direct beam solar irradiance. Swift (1976) presented an algorithm for calculating daily total solar irradiance on mountain slopes. This algorithm is suitable for use as a computer subroutine, making the use of tables unnecessary. Formulas for calculating direct beam irradiance presented by Frank and Lee (1966), Gates (1980), and Lee (1978) are useful, but they require more extensive development by the user for routine prediction of irradiance. Furthermore, the formulas are considered mainly in the context of total incoming shortwave irradiance.

This paper has two objectives. First, the formulas used by Frank and Lee (1966), Buffo et al. (1972), and Swift (1976) are extended to provide more details of the calculation procedures, particularly with regard to determinations of hour angles for calculating sunrise, sunset, and radiation and of the effects of intervening obstruction by terrain. This is done to facilitate the use of computers for calculations of both instantaneous and total direct beam irradiance. The reader is referred to the programs listed in the appendixes and to Swift's (1976) algorithm for linking the calculations.[3]

Second, the formulas are presented as a general case for direct beam solar irradiance, where the incoming irradiance may be total shortwave, visible, ultraviolet, etc., as selected by the user. In effect, the formulas for instantaneous and total irradiance yield a "multiplication factor" to be taken times the potential irradiance (e.g., the solar constant for total solar shortwave irradiance, approximately 2,600 $\mu E \cdot m^{-2} \cdot sec^{-1}$ for 400 to 700 nm irradiance, etc.). Duffie and Beckman (1974) provide data from several sources describing the standard spectral distribution of extraterrestrial irradiance. It must be recognized that the calculation procedures given below pertain only to the determination of irradiance above the atmosphere. Atmospheric effects on actual irradiance received at a surface in question must be determined for the appropriate portion of the solar spectrum of interest.

Abbreviations

M_o	potential irradiance constant (given a dimensionless value of 1.0 for a surface above the atmosphere, perpendicular to the sun's rays, at the equinox)
R_o	potential irradiance constant in user's units
M_i	multiplier for instantaneous irradiance for a given latitude, aspect, inclination, time of year, and time of day
R_i	instantaneous irradiance in user's units
M_t	multiplier for total daily irradiance from sunrise to sunset for a given latitude, aspect, inclination, and time of year

[3]*For those who have access to a Hewlett Packard 41C hand calculator, a Users' Library Solutions Manual for Solar Engineering (No. 00041-90138) has a program for solar-beam irradiation.*

R_t total daily irradiance in user's units
r radius vector, the ratio of the distance between the sun and earth at a given date to the mean distance
n Julian date
m month of year (1 to 12)
d day of month
θ latitude in degrees of the given slope, positive in northern hemisphere, negative in southern hemisphere
θ' latitude of the equivalent slope
δ solar declination in degrees for the given slope
α change in hour angle in degrees from the given to the equivalent slope
ω angular velocity of the earth's rotation ($15° \cdot hr^{-1}$)
t time in hours from solar noon
t_1 sunrise at the given slope
t_2 sunset at the given slope
t'_1 sunrise at the equivalent slope
t'_2 sunset at the equivalent slope
t'' time at the equivalent slope for calculating instantaneous irradiance
a azimuth of the slope in degrees measured clockwise from north
i inclination of the slope, 0° to 90°
A solar altitude in degrees
A′ solar azimuth in degrees measured clockwise from south

Equations

Horizontal Surfaces

The basic equation for calculating instantaneous irradiance on a horizontal surface outside the atmosphere is given by Frank and Lee (1966):

$$R_i = \frac{R_o}{r^2} (\sin\theta \cdot \sin\delta + \cos\theta \cdot \cos\delta \cdot \cos\omega t). \quad [1]$$

The value of r^2 ranges from 0.96676 on January 3 to 1.03370 on July 5 (List 1971, table 169). As an approximation, r^2 can be estimated by first determining the Julian date and declination as follows:

$$n = 31(m-1) + d - 0.4\,m - 1.8. \quad [2]$$

Round n to the nearest day. If m is 1 (January), add 2 to n. If m is 2 (February), add 3 to n. In leap years, add 1 day if m is 3 or greater (Ball 1978).

Solar declination can be estimated:

$$\delta = 23.5 \cdot \sin[0.9863(284 + n)]. \quad [3]$$

Finally, r^2 is calculated:

$$r^2 = 0.999847 + 0.001406(\delta). \quad [4]$$

By these procedures, δ is estimated within $+0.73°$ to $-1.38°$, and r^2 is estimated within $+0.84\%$ to -0.70%, depending upon time of year.

Multipliers for instantaneous irradiance may be calculated with a formula similar to equation 1:

$$M_i = \frac{M_o}{r^2} (\sin\theta \cdot \sin\delta + \cos\theta \cdot \cos\delta \cdot \cos\omega t) \quad [5]$$

where M_o is assigned a value of 1.0 at the equinox. In later illustrations, values of M_i are plotted as a function of several variables. The user may calculate instantaneous irradiance using a selected R_o as follows:

$$R_i = M_i R_o. \quad [6]$$

For a horizontal surface, if the sum of the absolute values of θ and δ is less than or equal to 90°, the hour angles of sunrise ($-\omega t$) and sunset (ωt) before and after solar noon can be found as follows:

$$\omega t = \cos^{-1}(-\tan\theta \cdot \tan\delta). \quad [7]$$

However, if the sum of the absolute values of θ and δ is greater than 90°, then the sun remains either above or below the horizon all day. If θ and δ have the same sign, the sun remains above the horizon and ωt equals 180°. If θ and δ have different signs, the sun is below the horizon for the day and $\omega t = 0°$.

Times for sunrise (t_1) and sunset (t_2) in hours before or after mean true solar noon are given by:

$$t_2 = -t_1 = \omega t/15. \quad [8]$$

The solar times calculated above are mean solar times. True solar time differs from mean solar time by an amount that varies through the year. True solar time may be calculated by algebraically adding a correction, called the equation of time, which ranges from -14 to $+16$ minutes (List 1971, table 169). Frank and Lee (1966) give procedures for converting solar time to local standard time.

Multipliers for total irradiance for a solar day may be calculated by integrating equation [5]:

$$M_t = (M_o/r^2)[2t \cdot \sin\theta \cdot \sin\delta + (12/\pi) \cdot \cos\theta \cdot \cos\delta \cdot 2 \cdot \sin\omega t]. \quad [9]$$

The user may calculate total irradiance using a selected R_o as follows:

$$R_t = M_t \cdot R_o. \quad [10]$$

Note that M_t has time units of hours; therefore R_o should have units of hours.

An example set of calculations for a horizontal surface is given in the Appendix (example 1).

Tilted Surfaces

When a surface is not horizontal, an "equivalent" horizontal surface exists at a higher or lower latitude and longitude which is parallel to the given surface. This equivalent surface is used to calculate the instantaneous and total irradiance received on the given surface. The next series of formulas, extending those of Frank and Lee (1966, citing earlier references), determine the location of the equivalent surface. Refer to figure 1 for a depiction of a given and equivalent slope.

The latitude of the equivalent surface is determined as follows:

$$\theta' = \sin^{-1}(\sin i \cdot \cos a \cdot \cos\theta + \cos i \cdot \sin\theta) \qquad [11]$$

where inclination is in degrees and azimuth is 0° to 360°. If inclination is given in percent slope, then:

$$i = \tan^{-1}(\%\ \text{slope}/100). \qquad [12]$$

The longitudinal correction of hour angle for the equivalent surface is given by:

$$\alpha = \tan^{-1}[(\sin a \cdot \sin i) \div (\cos i \cdot \cos\theta - \cos a \cdot \sin i \cdot \sin\theta)] \qquad [13]$$

when a is greater than 0°.

Because the $\tan^{-1}$ of an angle is defined for angles between −90° and 90°, if the slope is east-facing and α is less than 0°, then α is added to 180°. If the slope is west-facing and α is greater than 0°, α is added to −180°. If a is 0° (due north) and the sum of $|\theta|$ and i is less than or equal to 90°, α equals 0°. However, if the sum of $|\theta|$ and i is greater than 90°, α equals 180°.

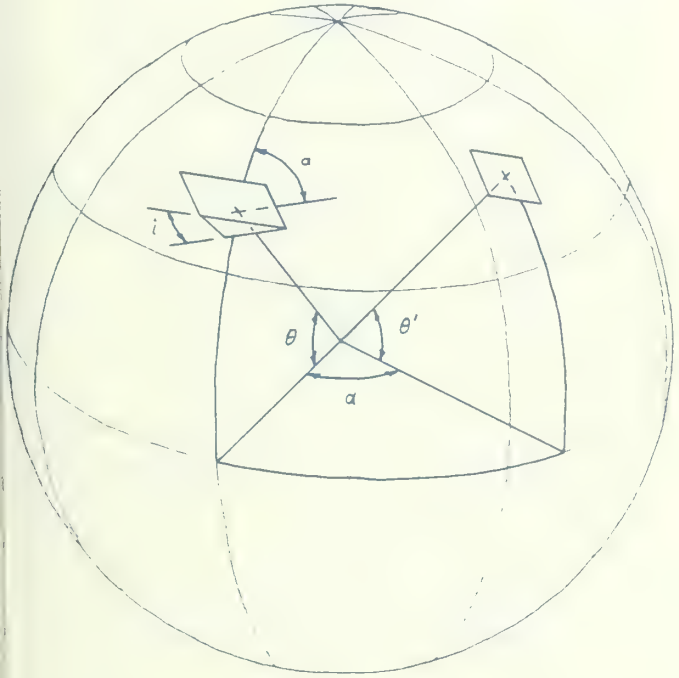

Figure 1.—Relation of given slope and equivalent slope. Given slope at latitude θ has azimuth a and inclination i. Equivalent slope has a different latitude, θ', and the longitude differs from that of the given slope by the hour angle, α.

Hour angles for sunrise and sunset at the equivalent surface are calculated the same way as those for horizontal slopes in equation [7], except that the equivalent latitude is used:

$$\omega t' = \cos^{-1}(-\tan\theta' \cdot \tan\delta). \qquad [14]$$

The same limits apply to $(-\tan\theta' \cdot \tan\delta)$ and $\omega t'$ using θ' as to $(-\tan\theta \cdot \tan\delta)$ and ωt for equation [7]. The special case of a double sunrise and sunset is considered later.

Hour angles for sunrise and sunset of the given slope may be determined as follows. If $(-\omega t + \alpha)$ is greater than or equal to $\omega t'$ (values from eq. [7], [13], and [14]), then the given slope is completely shaded throughout the day (t_1 and t_2 equal 0). If the slope is not completely shaded, the time of sunrise at the given slope then becomes:

$$t_1 = [\text{maximum of } (-\omega t) \text{ and } (-\omega t' - \alpha)] / 15. \qquad [15]$$

The time of sunset at the given slope becomes:

$$t_2 = [\text{minimum of } (\omega t) \text{ and } (\omega t' - \alpha)] / 15. \qquad [16]$$

Irradiance calculations for the equivalent surface require sunrise and sunset times for the equivalent surface. Sunrise for the equivalent slope is:

$$t_1' = [\text{maximum of } (-\omega t + \alpha) \text{ and } (-\omega t')] / 15. \qquad [17]$$

Sunset for the equivalent slope is:

$$t_2' = [\text{minimum of } (\omega t + \alpha) \text{ and } (\omega t')] / 15. \qquad [18]$$

Finally, irradiance multipliers can be calculated. Instantaneous irradiance is determined as follows:

$$M_i = \frac{M_o}{r^2}[\sin\theta' \cdot \sin\delta + \cos\theta' \cdot \cos\delta \cdot \cos(\omega t'')] \qquad [19]$$

where $\omega t'' = \omega t + \alpha$ and t is greater than or equal to t_1 and less than or equal to t_2. If t is less than t_1 or greater than t_2, then M_i equals 0.

A series of graphs discussed below present M_i as a function of latitude, azimuth, inclination, date, and time of day. Recalling equation [6], instantaneous irradiance in user units (R_i) can be determined as the product of M_i and R_o. Alternatively, the numerator value of M_o in equation [19] may be replaced with R_o.

Multipliers for total daily irradiance are calculated:

$$M_t = (M_o/r^2)[(t_2' - t_1') \cdot \sin\theta' \cdot \sin\delta + (12/\pi) \cdot \cos\theta' \cdot \cos\delta \cdot (\sin\omega t_2' - \sin\omega t_1')]. \qquad [20]$$

Total irradiance in user units (R_t) is determined as the product of M_t and R_o, or R_t may be determined by

substituting R_o for the numerator value of M_o in equation [20]. Values of R_t, using the solar constant as R_o, for a range of latitudes, azimuths, inclinations, and dates are tabulated in Frank and Lee (1966).

An example set of computations for a tilted surface is given in the Appendix (example 2).

Double Sunrise and Sunset

Steep, north-facing slopes and the north sides of buildings at middle latitudes in the northern hemisphere exhibit a sunrise and sunset both in the morning and in the afternoon. Double sunrises and sunsets occur when the following conditions are met:

$$(-\omega t') < (\omega t + \alpha - 360) < (-\omega t + \alpha) < (\omega t'). \quad [21]$$

If these conditions exist, sunrise and sunset times for the given slope are calculated as follows:

$$\text{First } t_1 = -\omega t / 15 \quad [22]$$
$$\text{First } t_2 = (\omega t' - \alpha) / 15 \quad [23]$$
$$\text{Second } t_1 = (360 - \omega t' - \alpha) / 15 \quad [24]$$
$$\text{Second } t_2 = \omega t / 15. \quad [25]$$

For calculating irradiance at the equivalent surface, sunrise and sunset times are:

$$\text{First } t_1' = -\omega t' / 15 \quad [26]$$
$$\text{First } t_2' = (\omega t + \alpha - 360) / 15 \quad [27]$$
$$\text{Second } t_1' = (-\omega t + \alpha) / 15 \quad [28]$$
$$\text{Second } t_2' = \omega t' / 15. \quad [29]$$

Calculation of the total daily irradiance multiplier for days having two sunrises and sunsets requires determining M_t using equation [20] for the first solar day (first t_1' to t_2') and for the second solar day (second t_1' to t_2'). These values are added to obtain the total daily irradiance multiplier. Again, total daily irradiance in user's units may be determined as the product of M_t and R_o or by replacing the numerator value of M_o with R_o in equation [20].

An example set of calculations for double sunrise and double sunset times is given in the Appendix (example 3). For radiation calculations on days of double sunrise and sunset, refer to example 2.

Obstruction of the Horizon

In mountainous regions, few sites are characterized by a direct view of the earth's horizon. Unless sites are located upon the highest ridgetops, intervening hills and ridges obscure the sun, resulting in later sunrises or earlier sunsets than those predicted by equation [8]. The delay of sunrise, advancement of sunset, or midday obstruction by intervening terrain (or objects) can be determined by comparing the elevation angle of the obstruction with the solar altitude. When the solar altitude at a given azimuth is below the obstruction altitude at the same azimuth, irradiance is set to zero.

Procedures for determining the solar altitude and azimuth are given by Lee (1978). The solar altitude is calculated as follows:

$$A = \sin^{-1}(\sin\theta \cdot \sin\delta + \cos\theta \cdot \cos\delta \cdot \cos\omega t). \quad [30]$$

Values of A less than 0° indicate that the sun is below the observer's true horizon, while values greater than 0° indicate that the sun is above the observer's true horizon.

The computation of solar azimuth is somewhat more difficult. Solar azimuths calculated below are determined clockwise from the observer's south. If $|\theta|$ is greater than $|\delta|$, the solar azimuth is given by

$$A' = \sin^{-1}(\cos\delta \cdot \sin\omega t / \cos A). \quad [31]$$

To establish the correct quadrant, first calculate the hour angle (H_w) at which the sun is due west of the observer:

$$H_w = \cos^{-1}(\tan\delta \cdot \operatorname{cotan}\theta). \quad [32]$$

Then, if $|\omega t|$ is less than or equal to H_w, A′ is in the correct quadrant. However, if $|\omega t|$ is greater than H_w, A′ is placed in the correct quadrant by

$$A' = \text{sign}(180, \omega t) - A' \quad [33]$$

where sign (180, ωt) is 180° if ωt is greater than or equal to 0 and −180° if ωt is less than 0°.

If $|\theta|$ is less than or equal to $|\delta|$, three possible cases exist. In the first case, $|\omega t|$ is greater than 0° but less than 180°. If δ equals 0°, then θ equals 0° and

$$A' = \text{sign}(90, \omega t). \quad [34]$$

If δ is not equal to 0°, then A′ is calculated as in equation [31]. A′ from equation [31] is in the correct quadrant if δ is less than 0°. For δ greater than 0°, A′ is determined using equation [33].

In the second case, ωt equals 0°. If $|\theta|$ equals $|\delta|$, then when θ is greater than or equal to 0°, A′ is 0°; when θ is less than 0°, A′ is 180°. If $|\theta|$ is less than $|\delta|$, then when δ is greater than 0°, A′ is 180°; when δ is less than 0°, A′ is 0°.

In the third case, $|\omega t|$ equals 180°. If $|\theta|$ equals $|\delta|$, then when θ is greater than or equal to 0°, A′ is 180°, and when θ is less than 0°, A′ is 0°. If $|\theta|$ is less than $|\delta|$, then when δ is greater than 0°, A′ is 180°, and when δ is less than 0°, A′ is 0°.

To determine the effects of intervening terrain, the terrain altitude and azimuth must be determined for the opposite horizon (east horizon for a slope having an azimuth of 0° to 180° and west horizon for a slope having an azimuth of 180° to 360°). This may be done by mapping the elevation angle of the horizon at suitably spaced azimuths or by calculating the elevation angle using topography maps.

At some sites, such as lower, south-facing slopes in valleys (northern hemisphere), the entire horizon between the points of sunrise and sunset must be mapped to determine if the sun is obstructed by the opposite ridge. The portion of the obstructed horizon which must be mapped and the azimuth difference between points at which elevation angle is measured will depend upon the particular site in question and the accuracy required.

After the terrain profile is determined, solar altitude is compared with the terrain elevation at various solar azimuths to determine the times at which the obstruction occludes the sun. For instantaneous irradiance calculations, M_i or R_i is set to zero if the solar altitude is less than the elevation angle of the terrain. For total daily irradiance, M_t or R_t are calculated using t_1' and t_2' adjusted for the effects of slope at the given site and for the effects of terrain elevation.

Explanation of Irradiance Figures

A series of graphs was prepared to illustrate how the instantaneous irradiance multiplier is influenced by latitude, date, azimuth (aspect), inclination (percent slope), and time of day. Three figures are presented for each of three latitudes—30°, 40°, and 50° N. These figures are for June 22, March or September 22, and December 22, representing the summer solstice, vernal and autumnal equinoxes, and winter solstice in the northern hemisphere. Slopes in degrees are as follows: 0% (0°), 20% (11.3°), 50% (26.6°), 100% (45°), 200% (63.4°), 400% (76.0°). Effects of obstructed opposite horizons are not taken into account.

The figures illustrate the complex geometric relationships among latitude, solar declination, azimuth, inclination, and hour angle. Total day length decreases from June 22 to December 22, but the change in day length is greatest at high latitudes. For example, at 30° N latitude, day length decreases from 13.9 hours to 10.1 hours (figs. 2 and 4), while at 50° N latitude, day length decreases from 16.2 hours to 7.8 hours (figs. 8 and 10).

Vertical dashed lines in the figures represent sunrises or sunsets at the true horizon for surfaces tilted east or west. For east-facing surfaces (azimuth of 90°), an increase in slope increases the intensity of radiation immediately after the sun rises past the horizon. However, steeper slopes also experience earlier sunsets because the effective horizon is elevated. Opposite effects occur on west-facing slopes.

Instantaneous irradiance of north-facing slopes (azimuth of 0°) at solar noon decreases as the inclination increases. At steep inclinations, the sun may set in the morning and rise in the afternoon during summer months; this effect becomes more pronounced at higher latitudes (compare figs. 2, 5, 8). During winter months, low sun angles prevent any direct beam radiation from reaching steep, north-facing slopes (figs. 4, 7, 10). On south-facing slopes (azimuth of 180°), instantaneous irradiance is often higher than on horizontal surfaces, because the normal to the slope is close to the solar beam pathway.

Figures 2 through 10 are presented only to demonstrate the effects of various factors which influence instantaneous irradiance. Through proper use of the equations given above, the user may calculate instantaneous irradiance for any latitude, date, azimuth, or inclination. In the southern hemisphere, instantaneous irradiance multipliers for slopes facing directly east or west are similar to those shown in the figures. However, for north- and south-facing slopes, the graphs are reversed.

The total irradiance multiplier (M_t), calculated with appropriate equations above, is represented by the area under the curves between sunrise and sunset. Frank and Lee (1966) tabulated total daily irradiance for latitudes between 30° and 50° N, 16 azimuths, and slopes from 0% to 100% for various times of the year. Their values were calculated with a solar irradiance constant of $2.0\,\text{cal} \cdot \text{cm}^{-2} \cdot \text{min}^{-1}$. Irradiance multipliers for total solar irradiance (M_t) are equal to Frank and Lee's values divided by 120 (from $2\,\text{cal} \cdot \text{cm}^{-2} \cdot \text{min}^{-1}$ times 60 min). Tabulated values of Buffo et al. (1972) include an atmospheric transmission coefficient and cannot be compared directly with those given here or in Frank and Lee (1966).

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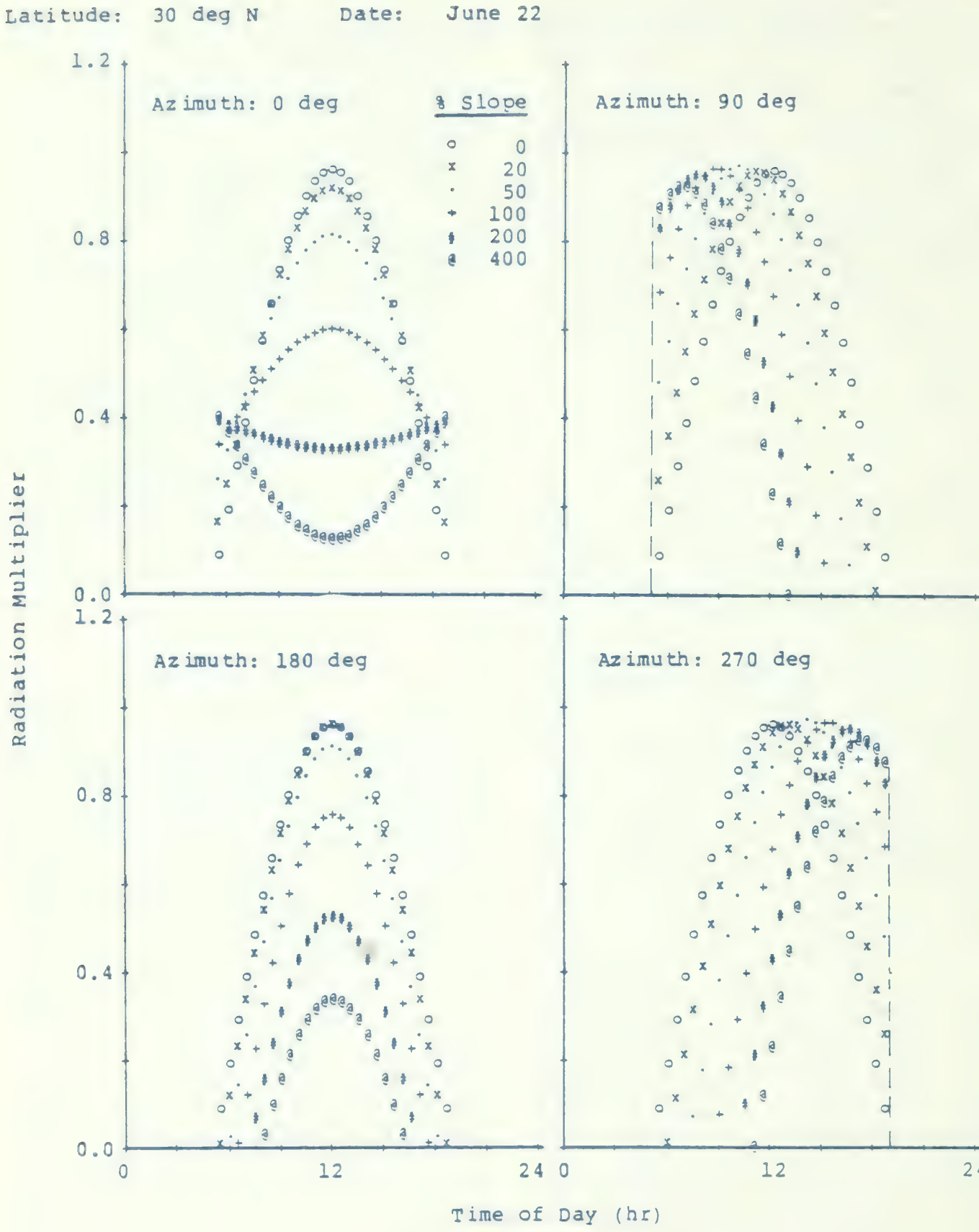

Figure 2.—Instantaneous irradiance multiplier for 30° N latitude on June 22.

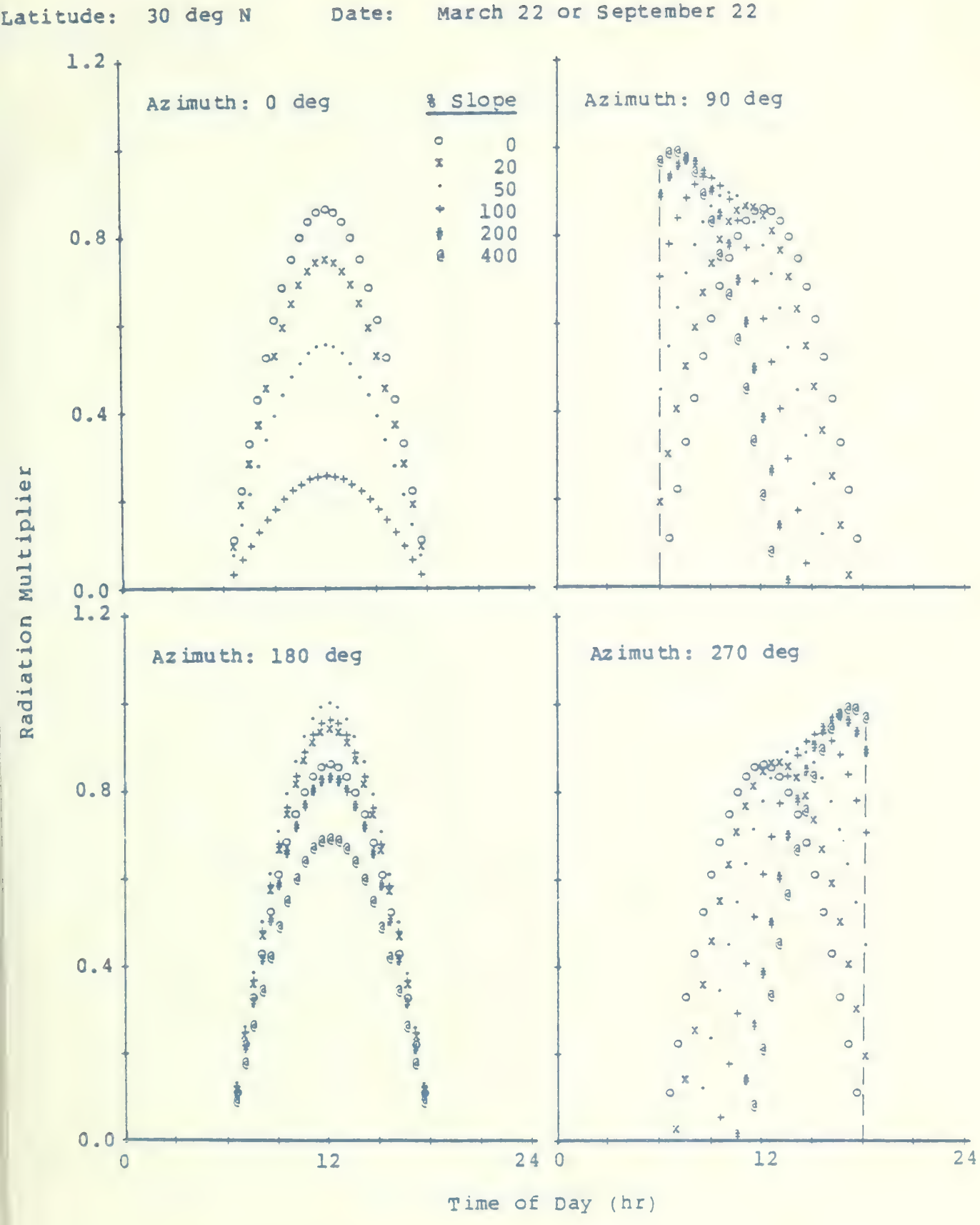

Figure 3.—Instantaneous irradiance multiplier for 30° N latitude on March 22 or September 22.

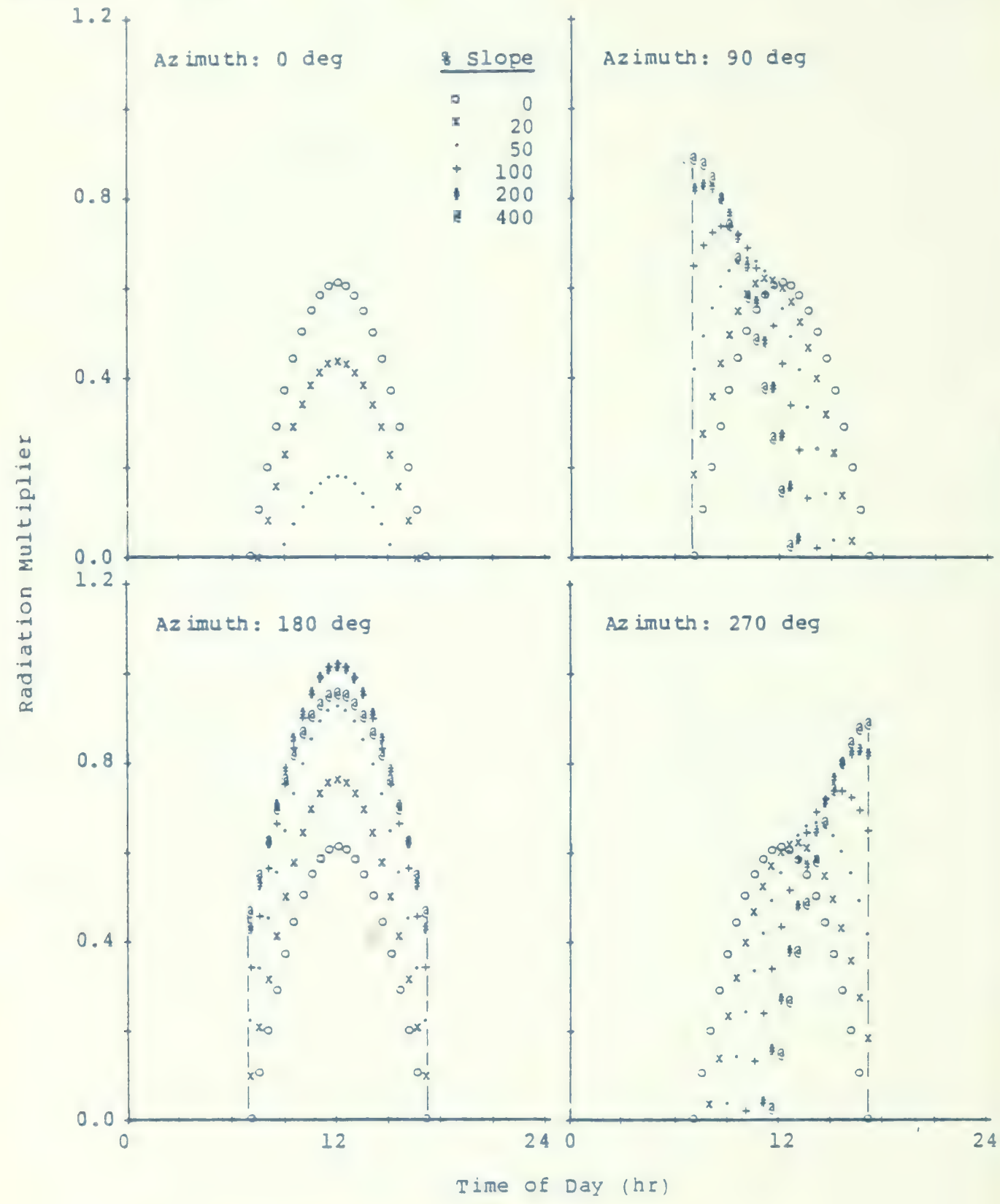

Figure 4.—Instantaneous irradiance multiplier for 30° N latitude on December 22.

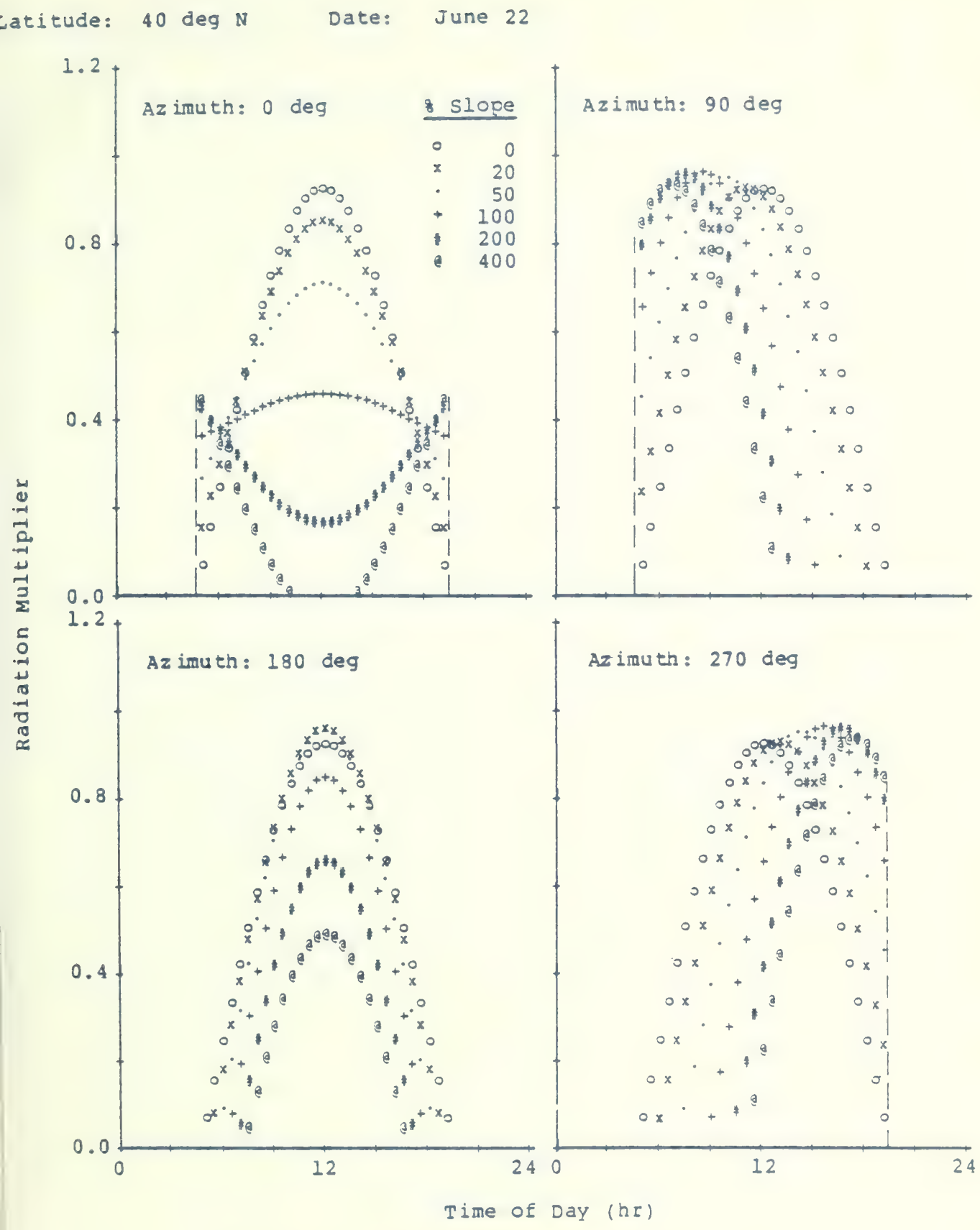

Figure 5.—Instantaneous irradiance multiplier for 40° N latitude on June 22.

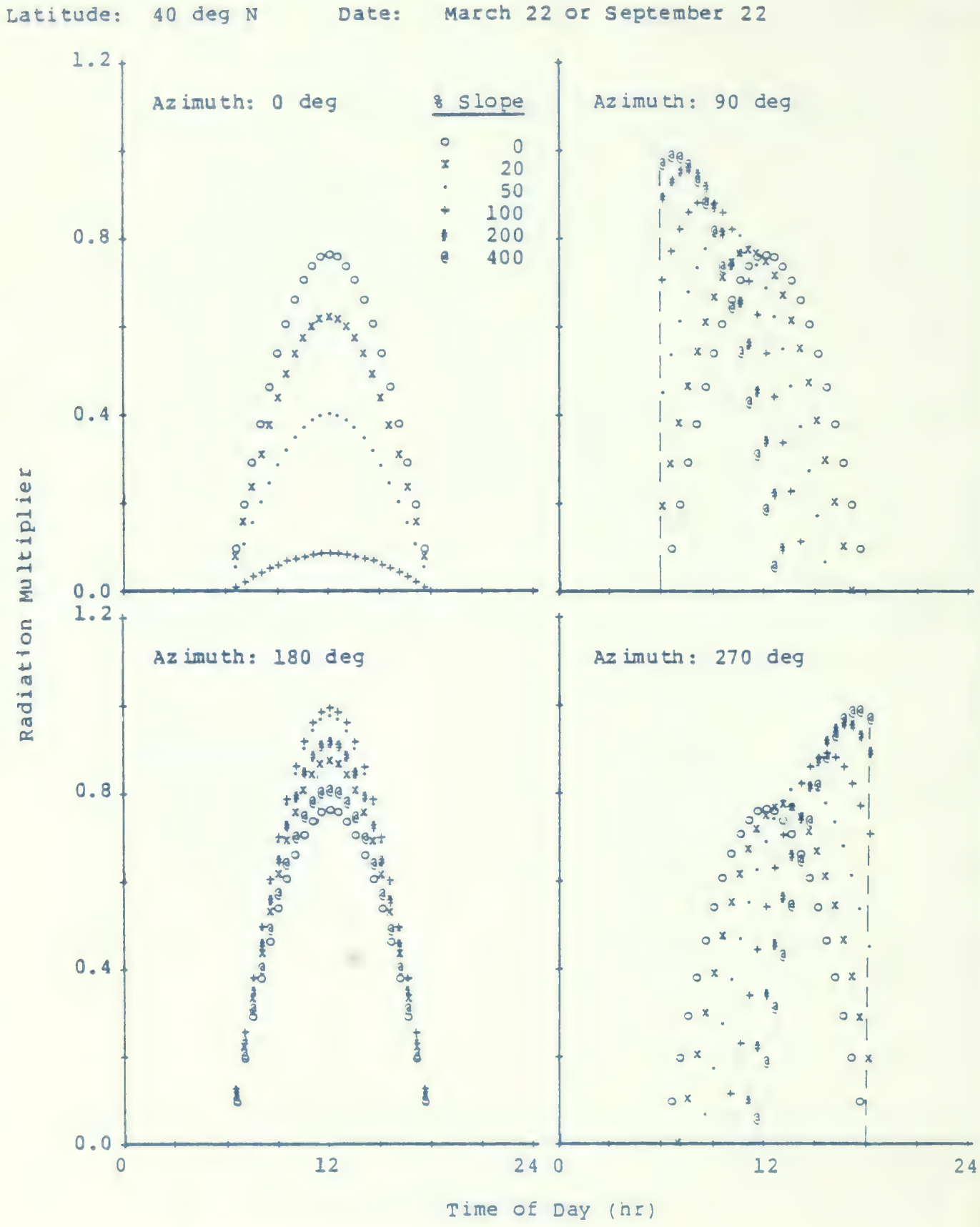

Figure 6.—Instantaneous irradiance multiplier for 40° N latitude on March 22 and September 22.

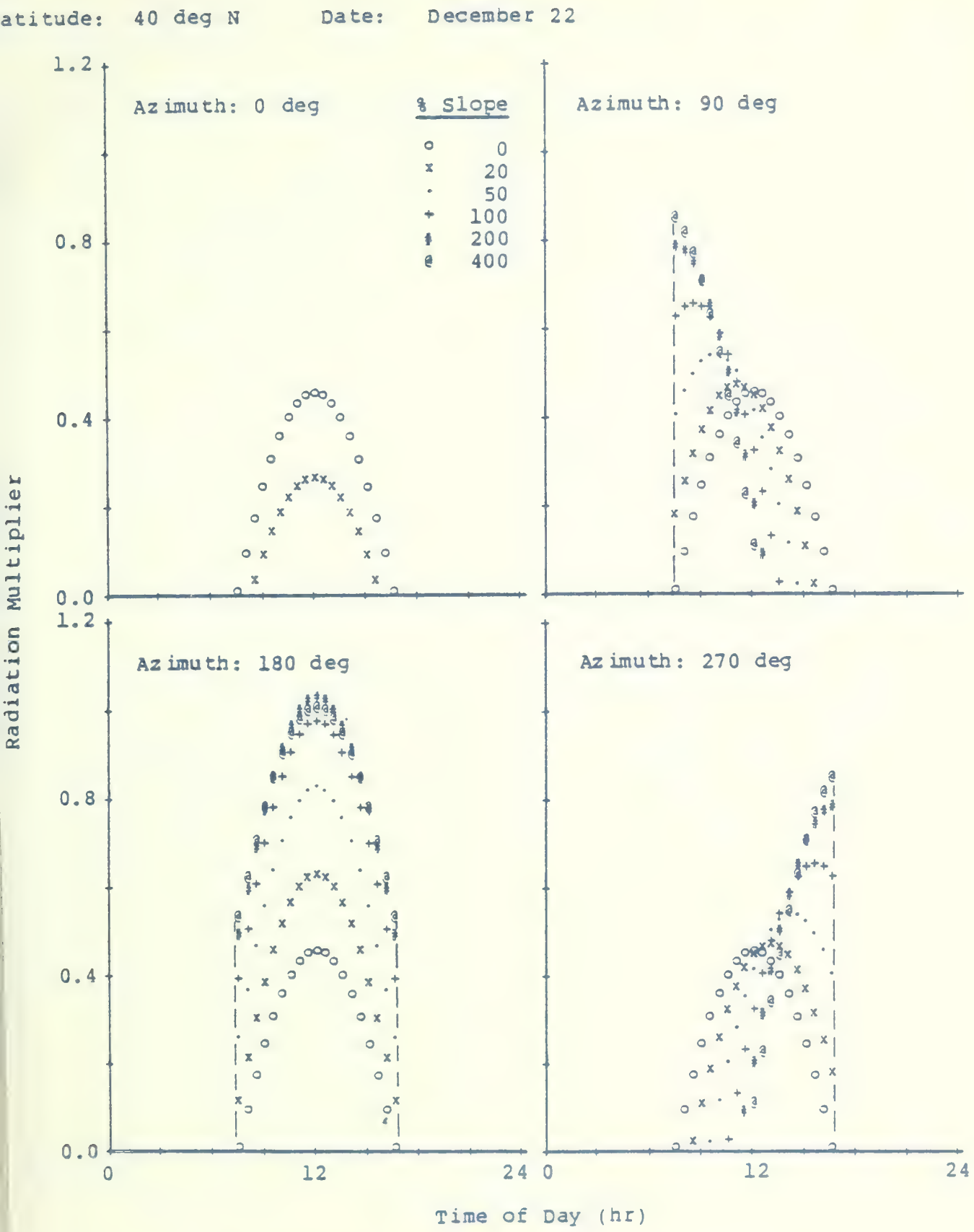

Figure 7.—Instantaneous irradiance multiplier for 40° N latitude on December 22.

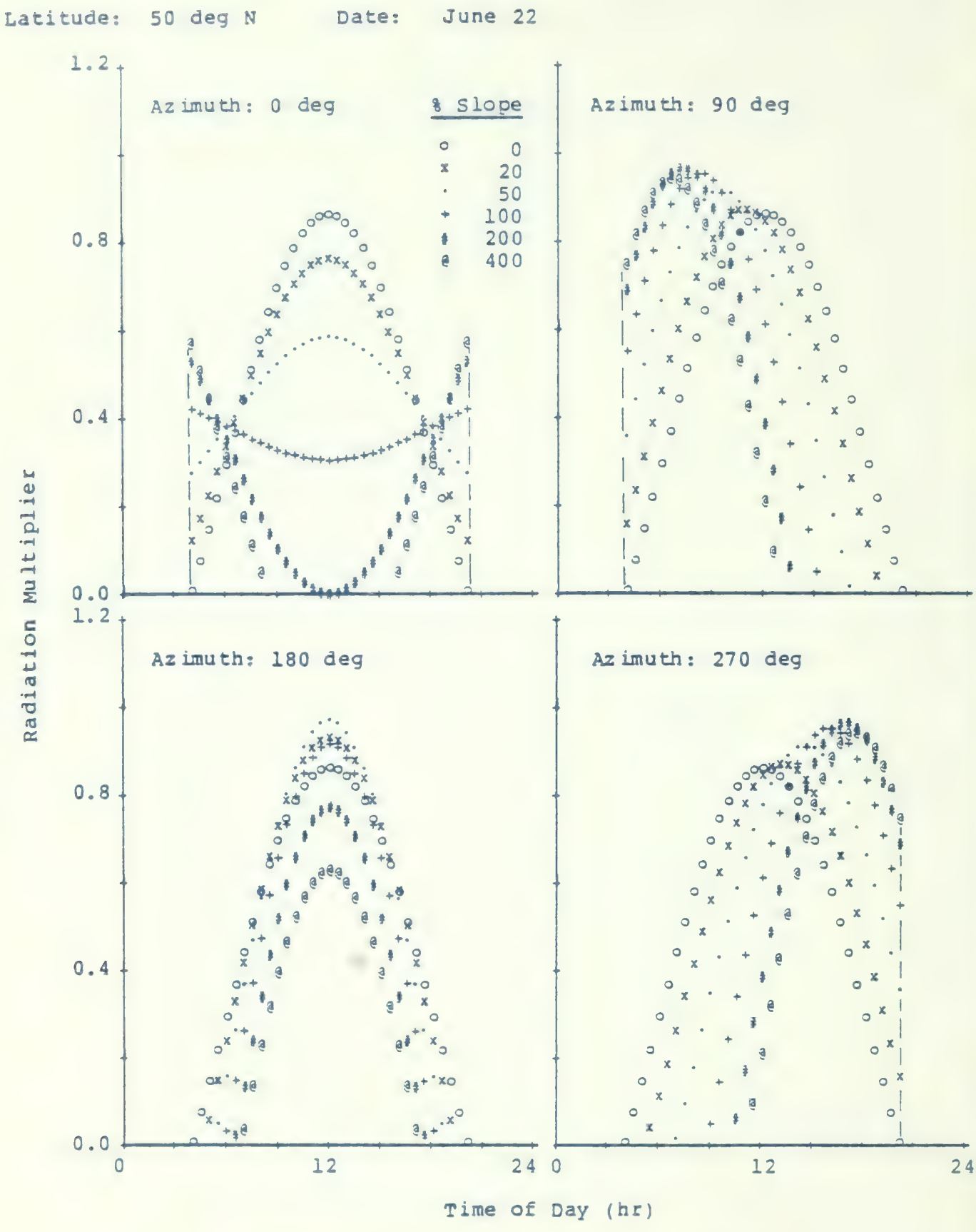

Figure 8.—Instantaneous irradiance multiplier for 50° N latitude on June 22.

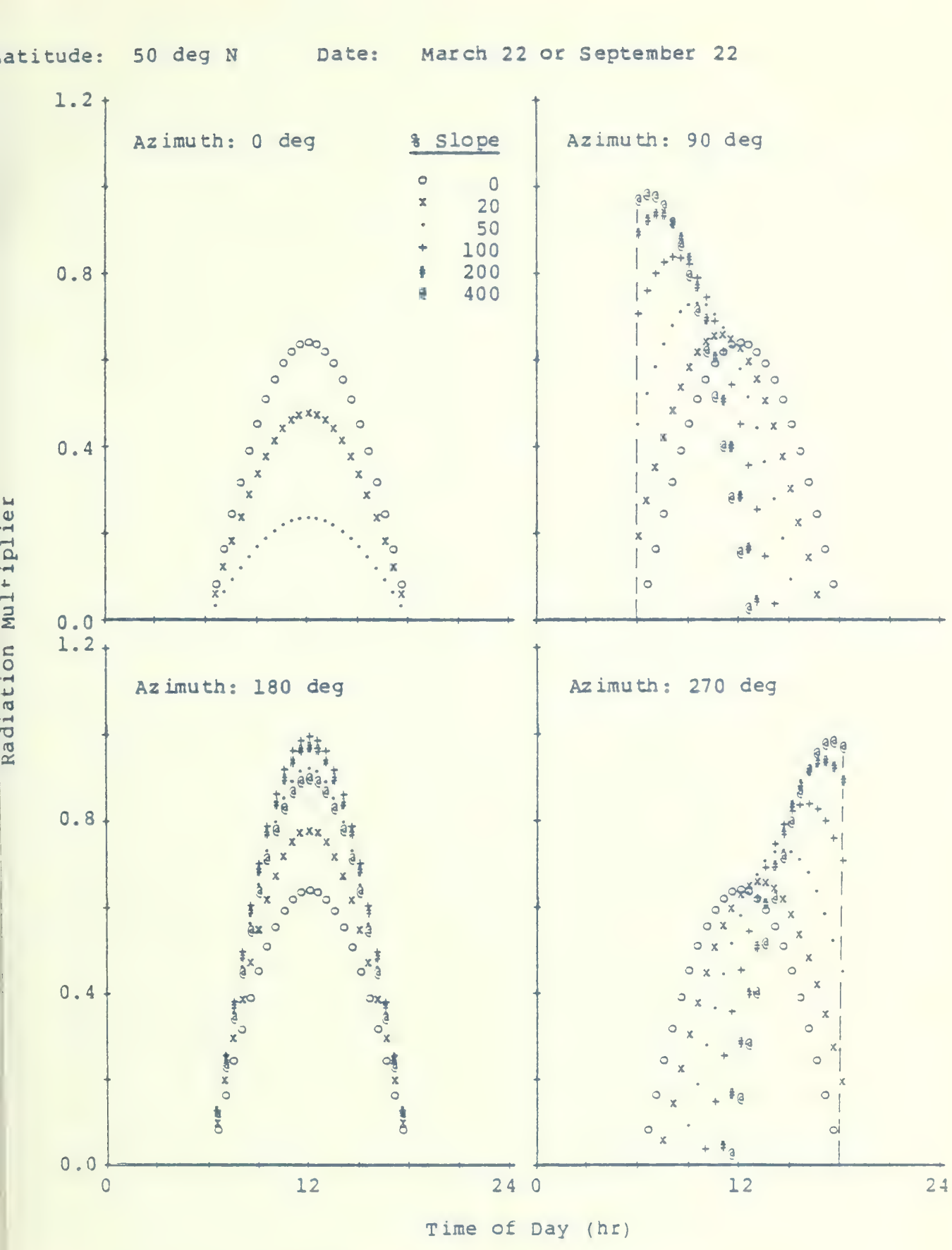

Figure 9.—Instantaneous irradiance multiplier for 50° N latitude on March 22 or September 22.

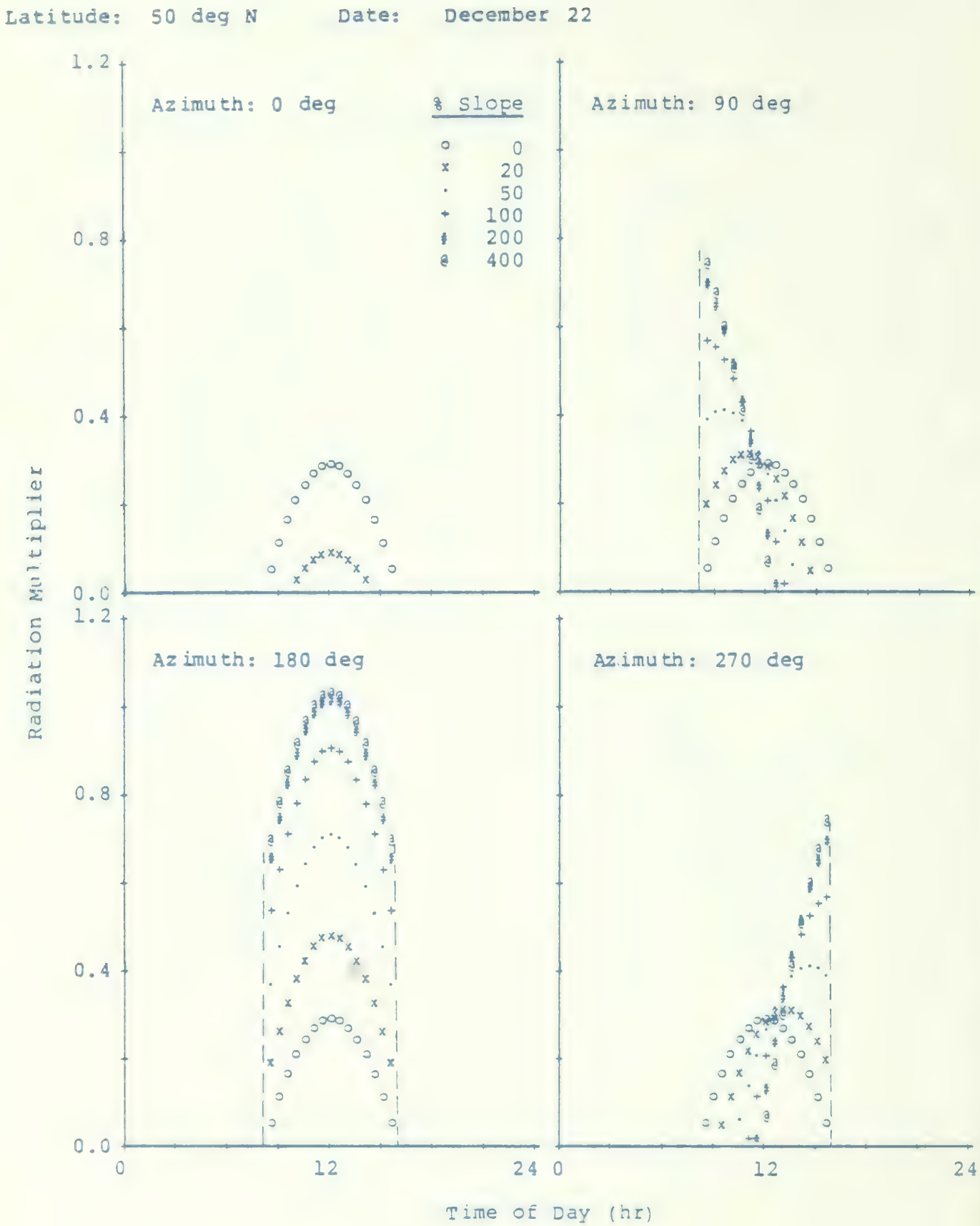

Figure 10.—Instantaneous irradiance multiplier for 50° N latitude on December 22.

Appendix A

xample 1.—Horizontal Surface

ate June 22
θ 40°
δ 23.5°
R_o 1360 W · m^{-2} (1.95 cal · cm^{2} · min^{-1})
t −2.00 hr (1000 hr)

imes of Sunrise and Sunset:

$$\omega t = \cos^{-1}(-\tan 40° \cdot \tan 23.5°)$$
$$t_2 = 7.43 \text{ hr (1926 hr)}$$
$$t_1 = -7.43 \text{ hr (0434 hr)}$$

nstantaneous Irradiance Multiplier:

$$\omega t = -2 \cdot 15° = -30°$$
$$M_i = 1.0[\sin 40° \cdot \sin 23.5° + \cos 40° \cdot \cos 23.5° \cdot \cos(-30°)] \div (0.999847 + 0.001406 \cdot 23.5°)$$
$$M_i = 0.8372$$

nstantaneous Irradiance:

$$R_i = 0.8372 \cdot 1360 \text{ W} \cdot m^{2}$$
$$R_i = 1138.6 \text{ W} \cdot m^{-2}$$

otal Daily Irradiance Multiplier:

$$M_i = 1.0[2 \cdot 7.43 \cdot \sin 40° \cdot \sin 23.5° + (12/\pi) \cdot \cos 40° \cdot \cos 23.5° \cdot 2 \cdot \sin 111.4°] \div 1.0329$$
$$M_t = 8.5251$$

otal Daily Irradiance:

$$R_t = 8.5251 \cdot 60 \cdot 1360$$
$$R_t = 6.956 \times 10^5 \text{ W} \cdot m^{-2}$$

xample 2.—Tilted Surface

ate September 22
θ 40°
δ 0°
R_o 1360 W · m^{-2}
t 1.00 hr (1300 hr)
a 90°
i 40%

nclination in Degrees:

$$i = \tan^{-1}(40/100)$$
$$i = 21.8°$$

quivalent Latitude:

$$\theta' = \sin^{-1}(\sin 21.8° \cdot \cos 90° \cdot \cos 40° + \cos 21.8° \cdot \sin 40°)$$
$$\theta' = 36.64°$$

Hour Angle Correction:

$$\alpha = \tan^{-1}[(\sin 90° \cdot \sin 21.8°) \div (\cos 21.8° \cdot \cos 40° - \cos 90° \cdot \sin 21.8° \cdot \sin 40°)]$$
$$\alpha = 27.57°$$

Sunrise and Sunset Hour Angles on Equivalent Slope:

$$\omega t' = \cos^{-1}(-\tan 36.64° \cdot \tan 0°)$$
$$\omega t' = 90°$$
Also,
$$\omega t = \cos^{-1}(-\tan 40° \cdot \tan 0°)$$
$$\omega t = 90°$$

Sunrise and Sunset for the Given Slope:

$$t_1 = [\max(-90°, -117.57°)] / 15$$
$$t_1 = -6.00 \text{ hr (0600 hr)}$$
$$t_2 = [\min(90°, 62.43°)] / 15$$
$$t_2 = 4.16 \text{ hr (1610 hr)}$$

Sunrise and Sunset for the Equivalent Slope:

$$t_1' = [\max(-62.43°, -90°)] / 15$$
$$t_1' = -4.16 \text{ hr (0750 hr)}$$
$$t_2' = [\min(117.57°, 90°)] / 15$$
$$t_2' = 6.00 \text{ hr (1800 hr)}$$

Instantaneous Irradiance Multiplier:

$$\omega t'' = 15 \cdot 1.00 + 27.57°$$
$$\omega t'' = 42.57°$$
$$M_i = 1.0[(\sin 36.64° \cdot \sin 0°) + (\cos 36.64° \cdot \cos 0° \cdot \cos 42.57°)] \div (0.999847 + 0.001406 \cdot 0°)$$
$$M_i = 0.5910$$

Instantaneous Irradiance:

$$R_i = 0.5910 \cdot 1360 \text{ W} \cdot m^{-2}$$
$$R_i = 803.8 \text{ W} \cdot m^{2}$$

Total Daily Irradiance Multiplier:

$$M_t = 1.0\{(6.00 + 4.16) \cdot \sin 36.64° \cdot \sin 0° + (12/\pi) \cdot \cos 36.64° \cdot \cos 0° \cdot [\sin 90° - \sin(-62.43°)]\} \div (0.999847 + 0.001406 \cdot 0°)$$
$$M_t = 5.7827$$

Total Daily Irradiance:

$$R_t = 5.7827 \cdot 60 \cdot 1360 \text{ W} \cdot m^{-2}$$
$$R_t = 4.719 \times 10^5 \text{ W} \cdot m^{-2}$$

Example 3.—Double Sunrise and Sunset

Date June 22
θ 50°
δ 23.5°
a 0°
i 250%

Inclination in Degrees:

$i = \tan^{-1}(250/100)$
$i = 68.2°$

Equivalent Latitude:
$\theta' = \sin^{-1}(\sin 68.2° \cdot \cos 0° \cdot \cos 50° + \cos 68.2° \cdot \sin 50°)$
$\theta' = 61.8°$ (note: this latitude is on the opposite side of the North Pole from the given slope; see calculation for α below)

Hour Angle Correction:

$\theta + i = 50 + 68.2$
$\theta + i = 118.2$
Because $(\theta + i) > 90°$, $\alpha = 180°$
$\omega t = \cos^{-1}(-\tan 50° \cdot \tan 23.5°)$
$\omega t = 121.21°$
$\omega t' = \cos^{-1}(-\tan 61.8° \cdot \tan 23.5°)$
$\omega t' = 144.19°$

Times of Double Sunrise and Sunset at the Given Slope

first $t_1 = -121.21°/15$
first $t_1 = -8.08$ hr (0355 hr)
first $t_2 = (144.19° - 180°)/15$
first $t_2 = -2.39$ hr (0937 hr)

second $t_1 = (360° - 144.19° - 180°)/15$
second $t_1 = 2.39$ hr (1423 hr)
second $t_2 = 121.21°/15$
second $t_2 = 8.08$ hr (2005 hr)

Times of Double Sunrise and Sunset at the Equivalent Slope:

first $t_1' = -144.19°/15$
first $t_1' = -9.61$ hr (0223 hr)
first $t_2' = (121.21° + 180° - 360°)/15$
first $t_2' = -3.92$ hr (0805 hr)

second $t_1' = (-121.21° + 180°)/15$
second $t_1' = 3.92$ hr (1555 hr)
second $t_2' = 144.19°/15$
second $t_2' = 9.61$ hr (2137 hr)

Appendix B

```
C   THIS PROGRAM ILLUSTRATES THE USAGE OF SUBPROGRAMS
C
C        JULDAT
C        DEC
C        RADVEC
C        RAD
C        GT
C        QI
C        SOLALT
C        SOLAZ
C
C   BY CALCULATING A TOTAL IRRADIATION MULTIPLIER
C   AND A TABLE OF INSTANTANEOUS IRRADIATION
C   MULTIPLIERS, SOLAR ALTITUDES AND SOLAR AZIMUTHS
C   AT 1/4 HOUR INTERVALS FOR 24 HOURS BEGINNING
C   AT SOLAR MIDNIGHT (12 HOURS PAST SOLAR NOON).
C
C   REQUIRED INPUT:
C
C        LATITUDE OF THE SITE IN DEGREES
C        AZIMUTH OF THE SITE MEASURED IN DEGREES
C           CLOCKWISE FROM NORTH
C        SLOPE OF THE SITE IN %
C        INTEGER VALUE OF THE MONTH OF THE PREDICTION
C        INTEGER VALUE OF THE DAY OF MONTH OF THE
C           PREDICTION
C
C   ALL OUTPUT TIMES ARE IN HOURS BEFORE (LT 0) OR AFTER (GT 0)
C   SOLAR NOON.  ALL OUTPUT HOUR ANGLES ARE IN DEGREES
C   CLOCKWISE FROM THE UPPER MERIDIAN.  SOLAR AZIMUTHS ARE GIVEN
C   IN DEGREES CLOCKWISE FROM SOUTH.
C
C
      COMMON/PIE/PI,PI2,PI12,PI180
      DIMENSION GTIME(4),ETIME(4)
      INTEGER DAY
      REAL LAT
      LOGICAL SHADED,DOUBLE
      REAL IRRAD
C
C                                     SET VARIOUS MULTIPLES OF PI FOR
C                                     COMMON BLOCK PIE
C
      PI=4.*ATAN(1.)
      PI2=PI/2.
      PI12=PI/12.
      PI180=PI/180.
C
C                                     READ AND PRINT USER INPUT
C
   10 PRINT 100
  100 FORMAT(1H0,'ENTER LATITUDE IN DEGREES')
      READ(5,*,END=250) LAT
      PRINT 110
  110 FORMAT(1H0,'ENTER AZIMUTH AS DEGREES CLOCKWISE FROM NORTH')
      READ(5,*) AZMUTH
      PRINT 120
  120 FORMAT(1H0,'ENTER % SLOPE')
      READ(5,*) SLOPE
      PRINT 130
  130 FORMAT(1H0,'ENTER MONTH OF PREDICTION')
      READ(5,*) MONTH
      PRINT 140
  140 FORMAT(1H0,'ENTER DAY OF PREDICTION')
      READ(5,*) DAY
C
      PRINT 150, LAT,AZMUTH,SLOPE,MONTH,DAY
  150 FORMAT(1H0/1H ,'LATITUDE - ',F6.1,' DEGREES'/1H ,
     &               'AZIMUTH - ',F6.1,' DEGREES'/1H ,
     &               'SLOPE - ',F6.1,' %'/1H ,
     &               'DATE OF PREDICTION - ',I2,'/',I2)
C
C                                        SET   N - JULIAN DATE
C                                              D - SOLAR DECLINATION
C                                              R2- RADIUS VECTOR SQUARED
C
      N=JULDAT(MONTH,DAY)
      D=DEC(N)
      R2=RADVEC(D)
C                                        DIVISION BY PI180 CONVERTS
C                                        RADIANS TO DEGREES
      PRINT 160, N,D/PI180,SQRT(R2)
  160 FORMAT(1H0,'JULIAN DATE - ',I4/1H ,
     &           'DECLINATION - ',F6.1,' DEGREES'/1H ,
     &           'RADIUS VECTOR - ',F8.5)
C
C                                        CONVERT LATITUDE,AZIMUTH, AND
C                                        SLOPE TO RADIAN MEASURE
C
      RLAT=LAT*PI180
      A=AZMUTH*PI180
      SLP=ATAN(SLOPE/100.)
C
C                                        CALL TO RAD ROUTINE TO CALCULATE
C                                          THETA - EQUIVALENT LATITUDE
C                                          ALPHA - CHANGE IN LONGITUDE
C                                          GTIME - SUNRISE SUNSET AT GIVEN
C                                                  SLOPE
C                                          ETIME - SUNRISE SUNSET AT THE
C                                                  EQUIVALENT SLOPE
C                                        AND DETERMINE THE NUMBER OF
C                                        SUNRISE SUNSET PERIODS
C
      CALL RAD(RLAT,A,SLP,D,THETA,ALPHA,SHADED,DOUBLE,GTIME,ETIME)
C
      PRINT 170, THETA/PI180,ALPHA/PI180
  170 FORMAT(1H0,'LATITUDE OF EQUIVALENT SLOPE - ',F6.1,' DEGREES'/1H ,
     &           'CHANGE IN LONGITUDE - ',F7.1,' DEGREES')
C
C                                        CALCULATE RADIATION MULTIPLIERS
```

```
C                                       AND GENERATE TABLE
C
      IF(SHADED)  THEN
C                                       GO TO NEXT PROBLEM SINCE
C                                       SUN DOES NOT RISE
        PRINT 180
180     FORMAT(1H0/1H ,'SLOPE IS SHADED FOR ENTIRE DAY')
      ELSE
C                                       AT LEAST 1 SUNRISE SUNSET PERIOD
        IF(.NOT. DOUBLE)  THEN
C                                       ONE SUNRISE SUNSET PERIOD
C
C                                       DIVISION BY PI12 CONVERTS
C                                       HOUR ANGLES IN RADIANS TO
C                                       HOURS BEFORE OR AFTER SOLAR
C                                       NOON
          PRINT 190, (GTIME(I)/PI12,I=1,2),(ETIME(I)/PI12,I=1,2)
190       FORMAT(1H0/1H ,'GIVEN SLOPE SUNRISE',F6.1/1H ,
     &                      12X,       'SUNSET',F6.1/1H0,
     &                      'EQUIVALENT SLOPE SUNRISE',F6.1/1H ,
     &                      17X,             'SUNSET',F6.1)
        ELSE
C                                       DOUBLE DAY - IE TWO SUNRISE
C                                       SUNSET PERIODS
          PRINT 200, (GTIME(I)/PI12,I=1,4),(ETIME(I)/PI12,I=1,4)
200       FORMAT(1H0/1H ,'DOUBLE SUNRISE SUNSET'/1H0,
     &       'GIVEN SLOPE FIRST SUNRISE',F6.1/1H ,
     &          12X,        'FIRST SUNSET',F6.1/1H ,
     &          12X,        'SECOND SUNRISE',F6.1/1H ,
     &          12X,        'SECOND SUNSET',F6.1/1H0,
     &          'EQUIVALENT SLOPE FIRST SUNRISE',F6.1/1H ,
     &          17X,             'FIRST SUNSET',F6.1/1H ,
     &          17X,             'SECOND SUNRISE',F6.1/1H ,
     &          17X,             'SECOND SUNSET',F6.1)
        END IF
C                                       SET TRAD -TOTAL DAILY IRRADIATION
C                                                 MULTIPLIER FOR FIRST
C                                                 SUNRISE-SET PERIOD
        TRAD=GT(GTIME(1),ETIME(2),THETA,D,R2)
C                                       CALCULATE TRAD FOR SECOND
C                                       SUNRISE-SET PERIOD
        IF(DOUBLE)  TRAD=TRAD+GT(ETIME(3),ETIME(4),THETA,D,R2)
C
        PRINT 210, TRAD
210     FORMAT(1H0/1H ,'MULTIPLIER FOR TOTAL IRRADIATION - ',F6.2)
        PRINT 220
220     FORMAT(1H0/1H ,3X,'INSTANTANEOUS'/1H ,
     &      10X,'HOUR',5X,'SOLAR',4X,'SOLAR',4X,
     &      'IRRADIATION'/1H ,
     &      'TIME',5X,'ANGLE',3X,'ALTITUDE',2X,
     &      'AZIMUTH',4X,'MULTIPLIER')
C
C                                       CALCULATE TABLE OF SOLAR
C                                       ALTITUDES AND AZIMUTHS FOR
C                                       10 MINUTE INTERVALS
C
      DO 240 I=1,96
C                                       CALCULATE WT - HOUR ANGLE-RADIANS
        WT=(I-48) * (PI12/4.)
C                                       SET  ALT - SOLAR ALTITUDE
C                                            SAZ - SOLAR AZIMUTH
        ALT=SOLALT(WT,RLAT,D)
        SAZ=SOLAZ(WT,RLAT,D,ALT)
C                                       SET IRRAD-INSTANTANEOUS RADIATION
C                                                 MULTIPLIER
        IF(.NOT. DOUBLE  .OR.  WT .LE. GTIME(2))  THEN
C                                       EITHER 1 SUNRISE-GTIME(1) AND 1
C                                       SUNSET-GTIME(2) OR DOUBLE SUNRISE
C                                       SUNSET AND WT LE GTIME(2) SO IN
C                                       THE FIRST PERIOD  GTIME(1) TO
C                                       GTIME(2)
          IRRAD=GI(WT,GTIME(1),GTIME(2),THETA,ALPHA,D,R2)
        ELSE
C                                       DOUBLE DAY AND WT GT GTIME(2) SO
C                                       IN SECOND PERIOD GTIME(3) TO
C                                       GTIME(4)
          IRRAD=GI(WT,GTIME(3),GTIME(4),THETA,ALPHA,D,R2)
        END IF
C                                       CALCULATE MILITARY TIME OF DAY
        ITIME=(I/4)*40 + I*15
C                                       PRINT ONE LINE OF TABLE
        PRINT 230, ITIME,WT/PI180,ALT/PI180,SAZ/PI180,IRRAD
230     FORMAT(1H ,I4,4F10.2)
240   CONTINUE
      END IF
C                                       GO TO NEXT PROBLEM
      GO TO 10
C
C                                       END OF PROGRAM EXECUTION
C
250   STOP
      END
```

```
C     SUBROUTINE RAD(TH,A,SLP,D,THP,ALPHA,SHADED,DOUBLE,GTIME,ETIME)
C
C     PURPOSE :
C          GIVEN  TH     - LATITUDE OF A GIVEN SLOPE IN RADIANS
C                          (TH<0 FOR SOUTHERN HEMISPHERE  TH>0 FOR NORTHERN
C                          HEMISPHERE)
C                 A      - AZIMUTH CLOCKWISE FROM NORTH IN RADIANS OF THE GIVE
C                          SLOPE (0 LE A LT 360)
C                 SLP    - ANGLE OF INCLINATION OF THE GIVEN SLOPE IN RADIANS
C                          (0 LE SLP LE 90)
C                 D      - SOLAR DECLINATION IN RADIANS FOR THE PREDICTION DAY
C                          (-23.45 LE D LE 23.47)
```

```
C
C       THIS ROUTINE WILL CALCULATE
C
C            THP    - LATITUDE OF THE EQUIVALENT SLOPE IN RADIANS
C                     (THP LT 0 FOR SOUTHERN HEMISPHERE  THP GT 0 FOR
C                     NORTHERN HEMISPHERE)
C            ALPHA  - CHANGE IN LONGITUDE FROM THE GIVEN SLOPE TO THE
C                     EQUIVALENT SLOPE IN RADIANS (-180 LT ALPHA LE 180)
C            SHADED - IF SHADED=.TRUE. THE GIVEN SLOPE IS SHADED
C                     FROM THE SUN FOR THE ENTIRE DAY
C            DOUBLE - IF DOUBLE=.TRUE. THE GIVEN SLOPE EXPERIENCES
C                     A DOUBLE SUNRISE-SUNSET.  IF DOUBLE=.FALSE. AND
C                     SHADED=.FALSE. THE GIVEN SLOPE EXPERIENCES ONE
C                     SUNRISE AND ONE SUNSET
C            GTIME(1) - HOUR ANGLE OF THE FIRST SUNRISE AT THE
C                     GIVEN SLOPE IN RADIANS (-180 LE GTIME(1) LE 180)
C            GTIME(2) - HOUR ANGLE OF THE FIRST SUNSET AT THE
C                     GIVEN SLOPE IN RADIANS (-180 LE GTIME(2) LE 180)
C            GTIME(3) - HOUR ANGLE OF THE SECOND SUNRISE AT THE
C                     GIVEN SLOPE IN RADIANS (-180 LE GTIME(3) LE 180)
C            GTIME(4) - HOUR ANGLE OF THE SECOND SUNSET AT THE
C                     GIVEN SLOPE IN RADIANS (-180 LE GTIME(4) LE 180)
C            ETIME(1) - HOUR ANGLE OF THE FIRST SUNRISE AT THE
C                     EQUIVALENT SLOPE IN RADIANS (-180 LE ETIME(1) LE 180)
C            ETIME(2) - HOUR ANGLE OF THE FIRST SUNSET AT THE
C                     EQUIVALENT SLOPE IN RADIANS (-180 LE ETIME(2) LE 180)
C            ETIME(3) - HOUR ANGLE OF THE SECOND SUNRISE AT THE
C                     EQUIVALENT SLOPE IN RADIANS (-180 LE ETIME(3) LE 180)
C            ETIME(4) - HOUR ANGLE OF THE SECOND SUNSET AT THE
C                     EQUIVALENT SLOPE IN RADIANS (-180 LE ETIME(4) LE 180)
C
C       NOTE THAT IF SHADED=.TRUE. GTIME AND ETIME ARE MEANINGLESS.
C       IF SHADED=.FALSE. AND .DOUBLE=.FALSE. THEN GTIME(3), GTIME(4),
C       ETIME(3), AND ETIME(4) ARE MEANINGLESS.
C
C       ONCE THESE VARIABLES ARE COMPUTED THE USER MAY INCORPORATE
C       SUBPROGRAMS GI AND GT TO CALCULATE IRRADIATION MULTIPLIERS.
C
C  REQUIRED SUBPROGRAMS : NONE
C
C  PROGRAMMING NOTES :
C
C       USAGE - CALL RAD(TH,A,SLP,D,THP,ALPHA,SHADED,DOUBLE,GTIME,ETIME)
C
C       PARAMETER TYPES :
C
C            PARAMETERS TH,A,SLP,D,THP,ALPHA ARE SCALARS OF TYPE REAL
C            PARAMETERS SHADED,DOUBLE ARE SCALARS OF TYPE LOGICAL
C            PARAMETERS GTIME,ETIME ARE ONE DIMENSIONAL ARRAYS OF
C               TYPE REAL AND DIMENSION 4
C            ALL VARIABLES ARE SINGLE PRECISION
C
C       COMMON BLOCKS - COMMON/PIE/PI,PI2,PI12,PI180   WHERE
C            PI=4*ATAN(1)
C            PI2=PI/2
C            PI12=PI/12
C            PI180=PI/180
C
C
      SUBROUTINE RAD(TH,A,SLP,D,THP,ALPHA,SHADED,DOUBLE,GTIME,ETIME)
      COMMON/PIE/PI,PI2,PI12,PI180
      REAL TH,A,SLP,THP,ALPHA,GTIME(4),ETIME(4)
      LOGICAL SHADED,DOUBLE

C CALCULATE LAT OF EQUIV SLOPE - THP

      THP=SIN(SLP)*COS(A)*COS(TH)  +  COS(SLP)*SIN(TH)
      THP=ASIN(THP)

C CALCULATE CHANGE IN LONGITUDE - ALPHA

      IF(A .GT. 0.)  THEN
        SINA=SIN(A)
        ALPHA=COS(SLP)*COS(TH)  -  COS(A)*SIN(SLP)*SIN(TH)
        ALPHA=(SINA*SIN(SLP))/ALPHA
        ALPHA=ATAN(ALPHA)
        IF(SINA*ALPHA .LT. 0.)  THEN
          ALPHA=SIGN(PI,SINA)+ALPHA
        END IF
      ELSE
        IF((ABS(TH)+SLP) .GT. PI2)  THEN
          ALPHA=PI
        ELSE
          ALPHA=0.
        END IF
      END IF

C CALCULATE     WT - HOUR ANGLE OF SUNSET AT GIVEN SLOPE
C               WTP - HOUR ANGLE OF SUNSET AT EQUIVALENT SLOPE

      IF(ABS(TH)+ABS(D) .GT. PI2)  THEN
        IF(TH+D .LT. 0.)  THEN
          WT=0.
        ELSE
          WT=PI
        END IF
      ELSE
        WT=ACOS(-TAN(TH)*TAN(D))
      END IF
      IF(ABS(THP)+ABS(D) .GT. PI2)  THEN
        IF(THP+D .LT. 0.)  THEN
              WTP=0.
            ELSE
              WTP=PI
            END IF
          ELSE
            WTP=ACOS(-TAN(THP)*TAN(D))
          END IF

C     CALCULATE SUNRISE SUNSET HOUR ANGLES

          T1=-WTP
```

```
            T2=(WT+ALPHA)-(2.*PI)
            T3=-WT+ALPHA
            T4=WTP

            IF(T4 .LE. T3)  THEN
               SHADED=.TRUE.
               DOUBLE=.FALSE.
            ELSE
               SHADED=.FALSE.
               IF(T1 .LT. T2 .AND. T2 .LT. T3  .AND.  T3 .LT. T4)  THEN
                  DOUBLE=.TRUE.
                  GTIME(1)=-WT
                  GTIME(2)=WTP-ALPHA
                  GTIME(3)=(2.*PI) - (WTP+ALPHA)
                  GTIME(4)=WT
                  ETIME(1)=T1
                  ETIME(2)=T2
                  ETIME(3)=T3
                  ETIME(4)=T4
               ELSE
                  DOUBLE=.FALSE.
                  GTIME(1)=AMAX1(-WT,-WTP-ALPHA)
                  GTIME(2)=AMIN1(WT,WTP-ALPHA)
                  ETIME(1)=AMAX1(-WT+ALPHA,-WTP)
                  ETIME(2)=AMIN1(WT+ALPHA,WTP)
               END IF
            END IF
            RETURN
            END
```

```
C   REAL FUNCTION DEC(N)
C
C   PURPOSE :
C        GIVEN  N      -THE JULIAN DATE
C        THIS ROUTINE WILL CALCULATE THE CORRESPONDING SOLAR DECLINATION
C              IN RADIANS  (-23.45 LE DEC LE 23.45)
C
C   REQUIRED SUBPROGRAMS : NONE
C
C   PROGRAMMING NOTES :
C
C        USAGE - D=DEC(N)
C
C        PARAMETER TYPES :
C
C             PARAMETER N IS A SCALAR OF TYPE INTEGER
C
C        COMMON BLOCKS - COMMON/PIE/PI,PI2,PI12,PI180  WHERE
C             PI=4.*ATAN(1)
C             PI2=PI/2
C             PI12=PI/12
C             PI180=PI/180
```

```
C
C
C
      REAL FUNCTION DEC(N)
      COMMON/PIE/PI,PI2,PI12,PI180
      INTEGER N
C
      DEC=23.45*PI180*SIN(2.*PI*(284+N)/365.)
C
      RETURN
      END
```

```
C   INTEGER FUNCTION JULDAT(MONTH,DAY)
C
C   PURPOSE :
C        GIVEN  MONTH - MONTH FOR PREDICTION (1 LE MONTH LE 12)
C               DAY   - DAY OF MONTH FOR PREDICTION (1 LE DAY LE 31)
C        THIS ROUTINE WILL CALCULATE THE CORRESPONDING JULIAN DATE.
C
C   REQUIRED SUBPROGRAMS : NONE
C
C   PROGRAMMING NOTES :
C
C        USAGE - N=JULDAT(MONTH,DAY)
C
C        PARAMETER TYPES :
C
C             PARAMETERS MONTH,DAY ARE SCALARS OF TYPE INTEGER
C
C        COMMON BLOCKS : NONE
C
C
      INTEGER FUNCTION JULDAT(MONTH,DAY)
      INTEGER MONTH,DAY
C
      N=31*(MONTH-1) + DAY
      IF(MONTH .GT. 2)  THEN
         JULDAT=N + NINT(-.4*MONTH - 1.8)
      ELSE
         JULDAT=N
      END IF
      RETURN
      END
```

```
      REAL FUNCTION QI(TIME,SR,SS,THETA,ALPHA,DEC,R2)
C
C     PURPOSE :
C          GIVEN  TIME  - HOUR ANGLE IN RADIANS FROM SOLAR NOON
C                         AT THE GIVEN SLOPE (-180 LT TIME LE 180)
C                 SR    - HOUR ANGLE IN RADIANS OF SUNRISE AT THE
C                         GIVEN SLOPE (-180 LT SR LE 180)
C                 SS    - HOUR ANGLE IN RADIANS OF SUNSET AT THE
C                         GIVEN SLOPE (-180 LT SS LE 180)
C                 THETA - LATITUDE OF THE EQUIVALENT SLOPE IN RADIANS
C                         (-90 LE THETA LE 90)
C                 ALPHA - CHANGE IN LONGITUDE FROM THE GIVEN SLOPE TO THE
C                         EQUIVALENT SLOPE IN RADIANS (-180 LT ALPHA LE 180)
C                 DEC   - SOLAR DECLINATION IN RADIANS FOR A PARTICULAR DAY
C                         (-23.45 LE DEC LE 23.45)
C                 R2    - THE SQUARED RATIO OF THE EARTH-SUN DISTANCE
C                         TO ITS MEAN FOR A PARTICULAR DAY
C          THIS ROUTINE WILL CALCULATE AN INSTANTANEOUS IRRADIATION
C               MULTIPLIER CORRESPONDING TO HOUR ANGLE TIME.
C
C     REQUIRED SUBPROGRAMS : NONE
C
C     PROGRAMMING NOTES :
C
C          USAGE - IRRAD=QI(TIME,SR,SS,THETA,ALPHA,DEC,R2)
C
C          PARAMETER TYPES :
C
C           PARAMETERS TIME,SR,SS,THETA,ALPHA,DEC,R2 ARE SCALARS OF TYPE REAL
C
C          COMMON BLOCKS : NONE
C
C
        REAL FUNCTION QI(TIME,SR,SS,THETA,ALPHA,DEC,R2)
        REAL TIME,SR,SS,THETA,ALPHA,DEC,R2
C
        IF(TIME .LT. SR  .OR.  TIME .GT. SS)  THEN
           QI=0.
        ELSE
           WTPP=TIME + ALPHA
           TERM1=SIN(THETA)*SIN(DEC)
           TERM2=COS(THETA)*COS(DEC)*COS(WTPP)
           QI=(1.0/R2) * (TERM1 + TERM2)
C                                       THE RANGE OF QI IS MATHEMATICALLY
C                                       LIMITED TO  0 LE QI LE 1.  DUE TO
C                                       ROUNDOFF AND/OR CANCELLATION ERRORS
C                                       THE ABOVE STATEMENT MAY ASSIGN A
C                                       VALUE LESS THAN 0 OR GREATER THAN 1
C                                       TO QI.  THE FOLLOWING STATEMENTS
C                                       ALLEVIATE THE PROBLEM.
           IF(QI .LT. 0.)  QI=0.
           IF(QI .GT. 1.)  QI=1.
        END IF
        RETURN
        END
```

```
      REAL FUNCTION QT(SR,SS,THETA,DEC,R2)
C
C     PURPOSE :
C          GIVEN  SR    - HOUR ANGLE IN RADIANS OF SUNRISE AT THE
C                         SLOPE (-180 LE SR LE 180)
C                 SS    - HOUR ANGLE IN RADIANS OF SUNSET AT THE
C                         SLOPE (-180 LE SS LE 180)
C                 THETA - LATITUDE OF THE SLOPE IN RADIANS
C                         (-90 LE THETA LE 90)
C                 DEC   - SOLAR DECLINATION IN RADIANS FOR A PARTICULAR DA
C                         (-23.45 LE DEC LE 23.45)
C                 R2    - THE SQUARED RATIO OF THE EARTH-SUN DISTANCE
C                         TO ITS MEAN FOR A PARTICULAR DAY
C          THIS ROUTINE WILL CALCULATE A TOTAL IRRADIATION MULTIPLIER
C               CORRESPONDING TO HOUR ANGLES SR SS.
C
C     REQUIRED SUBPROGRAMS : NONE
C
C     PROGRAMMING NOTES :
C
C          USAGE - TRAD=QT(SR,SS,THETA,DEC,R2)
C
C          PARAMETER TYPES :
C
C               PARAMETERS SR,SS,THETA,DEC,R2 ARE SCALARS OF TYPE REAL
C
C          COMMON BLOCKS - COMMON/PIE/PI,PI2,PI12,PI180   WHERE
C               PI=4*ATAN(1)
C               PI2=PI/2
C               PI12=PI/12
C               PI180=PI/180
C
C
        REAL FUNCTION QT(SR,SS,THETA,DEC,R2)
        REAL SR,SS,THETA,DEC,R2
        COMMON/PIE/PI,PI2,PI12,PI180
C
        SSMSR=(SS-SR)*12./PI
        TERM1=SSMSR*SIN(THETA)*SIN(DEC)
        TERM2=COS(THETA)*COS(DEC)*(SIN(SS)-SIN(SR))
        QT=(1.0/R2)*(TERM1 + 12./PI*TERM2)
C                                       THE RANGE OF QT IS MATHEMATICALLY
C                                       LIMITED TO :
C
C                                       0   LE   QT   LE   (1/R2)(SSMSR*24/
C
C                                       DUE TO ROUNDING AND/OR CANCELLATION
C                                       ERRORS THE ABOVE STATEMENT MAY ASSI
C                                       A VALUE TO QT OUT OF THIS RANGE.  T
C                                       FOLLOWING STATEMENTS ALLEVIATE THE
C                                       PROBLEM.
        IF(QT .LT. 0.)  QT=0.
        IF(QT .GT. 1./R2*(SSMSR*24./PI)) QT=1./R2*(SSMSR*24./PI)
C
        RETURN
        END
```

```
      C   REAL FUNCTION RADVEC(D)
      C
      C   PURPOSE :
      C        GIVEN D      - THE SOLAR DECLINATION IN RADIANS
      C        THIS ROUTINE WILL CALCULATE THE SQUARED RATIO OF
      C             THE EARTH-SUN DISTANCE TO ITS MEAN FOR THE
      C             CORRESPONDING DAY.
      C
      C   REQUIRED SUBPROGRAMS : NONE
      C
      C   PROGRAMMING NOTES :
      C
      C        USAGE - R2=RADVEC(D)
      C
      C        PARAMETER TYPES :
      C
      C             PARAMETER D IS A SCALAR OF TYPE REAL
      C
      C        COMMON BLOCKS -> COMMON/PIE/PI,PI2,PI12,PI180   WHERE
      C             PI=4*ATAN(1)
      C             PI2=PI/2
      C             PI12=PI/12
      C             PI180=PI/180
      C
      C
        REAL FUNCTION RADVEC(D)
        COMMON/PIE/PI,PI2,PI12,PI180
        REAL )
      C
        RADVEC= 0.999847 + 0.001406 * (D/PI180)
      C
        RETURN
        END
```

```
      C   REAL FUNCTION SOLALT(WT,LAT,DEC)
      C
      C   PURPOSE :
      C        GIVEN  WT    - THE HOUR ANGLE IN RADIANS (-180 LE WT LE 180)
      C               LAT   - THE LATITUDE IN RADIANS OF A GIVEN SITE
      C                       (-90 LE LAT LE 90)
      C               DEC   - THE SOLAR DECLINATION IN RADIANS FOR A GIVEN DAY
      C                       (-23.45 LE DEC LE 23.45)
      C        THIS ROUTINE WILL CALCULATE THE SOLAR ALTITUDE IN RADIANS
      C             FROM THE TRUE HORIZON.
      C
      C   REQUIRED SUBPROGRAMS : NONE
      C
      C   PROGRAMMING NOTES :
      C
      C        USAGE - ALT=SOLALT(WT,LAT,DEC)
      C
      C        PARAMETER TYPES :
      C
      C             PARAMETERS WT,LAT,DEC ARE SCALARS OF TYPE REAL
      C
      C        COMMON BLOCKS : NONE
      C
      C
      C
        REAL FUNCTION SOLALT(WT,LAT,DEC)
        REAL WT,LAT,DEC
      C
        SINALT=COS(WT)*COS(LAT)*COS(DEC) + SIN(LAT)*SIN(DEC)
      C
      C                                  DUE TO ROUNDING AND/OR CANCELLATION
      C                                  ERRORS THE ABOVE STATEMENT MAY ASSIGN
      C                                  A VALUE LESS THAN -1 OR GREATER THAN 1
      C                                  TO SINALT CAUSING AN ERROR TERMINATION
      C                                  IN THE ASIN ROUTINE.  THE FOLLOWING
      C                                  STATEMENT ELIMINATES THIS PROBLEM.
      C
        SINALT=SIGN(AMIN1(ABS(SINALT),1.),SINALT)
      C
        SOLALT=ASIN(SINALT)
      C
        RETURN
        END
```

```
C   REAL FUNCTION SOLAZ(WT,LAT,DEC,ALT)
C
C   PURPOSE :
C        GIVEN  WT    - THE HOUR ANGLE IN RADIANS (-180 LE WT LE 180)
C               LAT   - THE LATITUDE IN RADIANS OF A GIVEN SITE
C                       (-90 LE LAT LE 90)
C               DEC   - THE SOLAR DECLINATION IN RADIANS FOR A GIVEN DAY
C                       (-23.45 LE DEC LE 23.45)
C               ALT   - THE SOLAR ALTITUDE IN RADIANS FROM THE
C                       TRUE HORIZON (-90 LE ALT LE 90)
C        THIS ROUTINE WILL CALCULATE THE SOLAR AZIMUTH IN RADIANS
C             MEASURED CLOCKWISE FROM SOUTH (0 LE SOLAZ LT 360).
C
C   REQUIRED SUBPROGRAMS : NONE
C
C   PROGRAMMING NOTES :
C
C        USAGE - AZ=SOLAZ(WT,LAT,DEC,ALT)
C
C        PARAMETER TYPES :
C
C             PARAMETERS WT,LAT,DEC,ALT ARE SCALARS OF TYPE REAL
C
C        COMMON BLOCKS - COMMON/PIE/PI,PI2,PI12,PI180   WHERE
C             PI=4*ATAN(1)
C             PI2=PI/2
C             PI12=PI/12
C             PI180=PI/180
C
C
      REAL FUNCTION SOLAZ(WT,LAT,DEC,ALT)
      REAL WT,LAT,DEC,ALT
      COMMON/PIE/PI,PI2,PI12,PI180
C
      ABSWT=ABS(WT)
      ABSLAT=ABS(LAT)
      ABSDEC=ABS(DEC)
      IF(ABS(ALT) .LT. PI2)  THEN
         SINSAZ=COS(DEC)*SIN(WT)/COS(ALT)
C
C                              WHEN WT AND ALT SHOULD DIFFER BY + OR - 90
C                              DEGREES BUT DONT DUE TO ROUNDOFF AND/OR
C                              CANCELLATION ERRORS THE ABOVE STATMENT
C                              MAY ASSIGN A VALUE LESS THAN -1 OR
C                              GREATER THAN +1 TO SINSAZ CAUSING AN
C                              ERROR TERMINATION IN THE ASIN ROUTINE.
C                              THE FOLLOWING STATEMENT ELIMINATES
C                              THIS PROBLEM.
C
         SINSAZ=SIGN(AMIN1(ABS(SINSAZ),1.),SINSAZ)
C
         SAZ=ASIN(SINSAZ)
      END IF
      IF(ABSLAT .GT. ABSDEC)  THEN
         HR=ACOS(TAN(DEC)*COTAN(LAT))
         IF(ABSWT .LE. HR)  THEN
            SOLAZ=SAZ
         ELSE
            SOLAZ=SIGN(PI,WT) - SAZ
         END IF
      ELSE
         IF(0. .LT. ABSWT  .AND.  ABSWT .LT. PI)  THEN
            IF(DEC .EQ. 0.)  THEN
               SOLAZ=SIGN(PI2,WT)
            ELSE IF(DEC .LT. 0.)  THEN
               SOLAZ=SAZ
            ELSE
               SOLAZ=SIGN(PI,WT)-SAZ
            END IF
         ELSE IF(ABSWT .EQ. PI)  THEN
            IF(ABSLAT .EQ. ABSDEC)  THEN
               IF(LAT .GE. 0)  THEN
                  SOLAZ=PI
               ELSE
                  SOLAZ=0.
               END IF
            ELSE
               IF(DEC .GT. 0.)  THEN
                  SOLAZ=PI
               ELSE
                  SOLAZ=0.
               END IF
            END IF
         ELSE
            IF(ABSLAT .EQ. ABSDEC)  THEN
               IF(LAT .GE. 0.)  THEN
                  SOLAZ=0.
               ELSE
                  SOLAZ=PI
               END IF
            ELSE
               IF(DEC .GT. 0.)  THEN
                  SOLAZ=PI
               ELSE
                  SOLAZ=0.
               END IF
            END IF
         END IF
      END IF
      IF(SOLAZ .LT. 0.)  SOLAZ=2.*PI + SOLAZ
C
      RETURN
      END
```

Rocky Mountains

Southwest

Great Plains

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Forest Service

Rocky Mountain Forest and Range Experiment Station

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Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

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Shelterbelt Establishment and Growth at a Windswept Wyoming Rangeland Site

David L. Sturges

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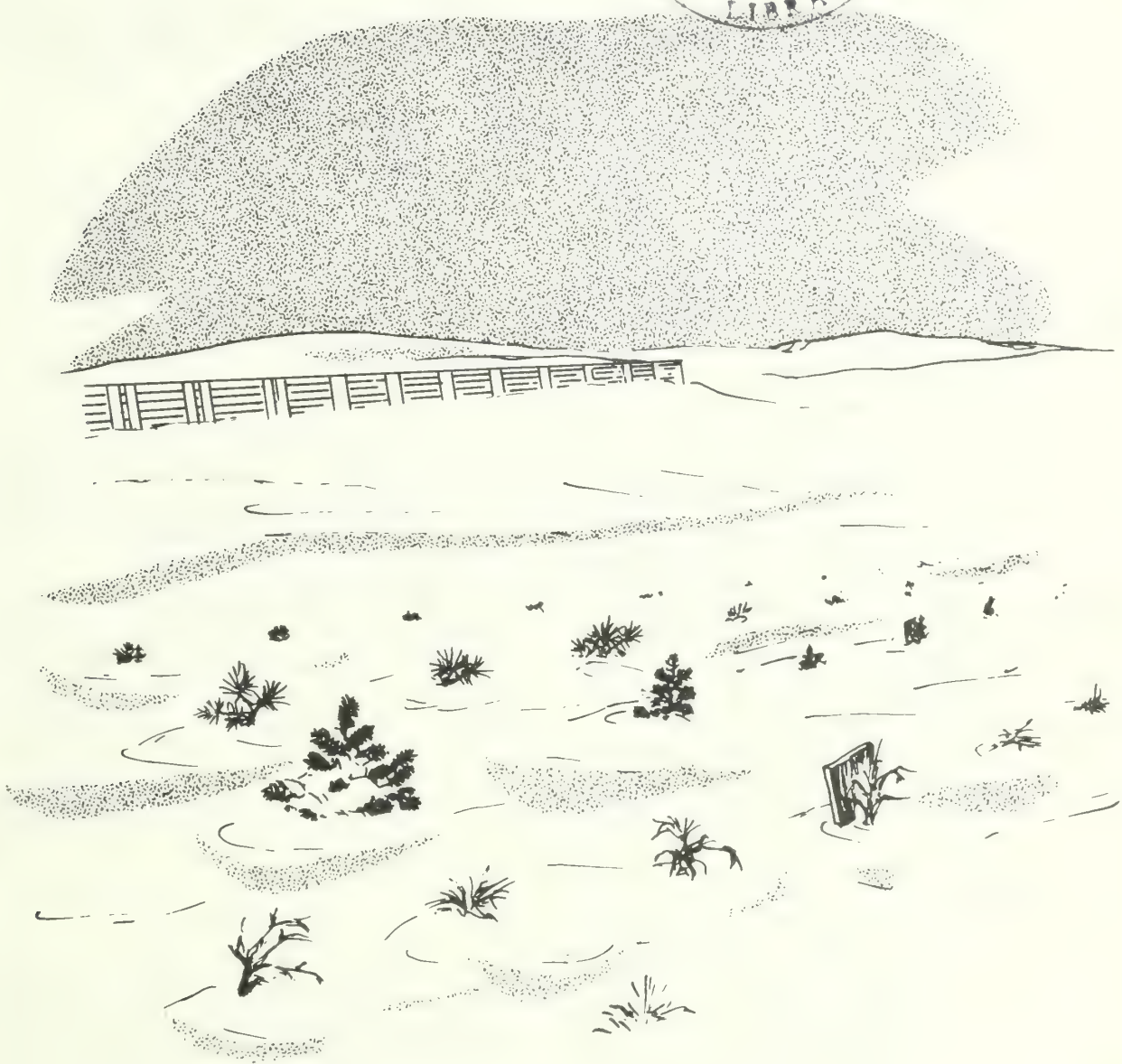

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Research Paper RM-243

February 19

Shelterbelt Establishment and Growth at a Windswept Wyoming Rangeland Site

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Abstract

Survival and growth of six shelterbelt tree and shrub species and three rangeland shrubs were evaluated for 5 years at a planting site adjacent to Interstate-80 in southcentral Wyoming. Depredation by rodents at the rangeland site limited establishment and growth of some species more severely than did the harsh climate.

[1]*Headquarters is in Fort Collins, in cooperation with Colorado State University; research reported here was conducted at the Station's Research Work Unit at Laramie, in cooperation with the University of Wyoming. Research was supported in part by the Wyoming Highway Department.*

Shelterbelt Establishment and Growth at a Windswept Wyoming Rangeland Site

David L. Sturges

Management Implications

This study indicates that shelterbelt tree and shrub species do not become large enough to serve as effective snow control agents for a number of years after planting. Three conifer species, initially 0.10 to 0.15 m tall, were 0.4 to 0.5 m tall after 5 years. Colorado blue spruce and ponderosa pine appeared equally well adapted to the harsh environmental conditions at the study site.

Russian olive was the most promising deciduous species for shelterbelt use, based on this study. It had a densely branched growth form, and lateral crown spread was approximately equal to plant height. Initial survival of Russian olive was low, but probably can be enhanced by using as parent stock plants that have shown adaptability to severe environmental stresses. Siberian peashrub is described as a vigorous and densely branched shrub when grown in shelterbelts on the High Plains of eastern Wyoming (Howard 1964, Edmondson 1951). However, at the study site it had a spindly growth form and should be planted closer than the 2.4-m spacing used in this study. The average height of Siberian peashrub exceeded all other species after 5 years, but most of this growth was in the first 3 years of the study.

White rabbitbrush was the only rangeland shrub that showed promise as a shelterbelt species. Its initial survival was low, which may be an artifact of the manner in which seedlings were handled prior to planting. Additional testing is required to improve establishment methods. Initial growth rates of Colorado and Nevada selections of basin big sagebrush were extremely rapid. However, a lack of winter hardiness prohibits use of this sagebrush subspecies where environmental conditions are similar to those at the study site.

The presence of an upwind snow fence to ameliorate wind speed did not influence either establishment success or the growth rate of conifer and deciduous shelterbelt species. Additional trials would be useful to verify this conclusion, because of limitations imposed by the study site. Such trials should be conducted where plantings can be made (a) outside of the area influenced by wind flow around the ends of a snow fence, and (b) at sufficient distance downwind from a snow fence to be free of the drift cast by the fence. Drifts cast by a Wyoming snow fence extend downwind for a distance of 29.5 times fence height when the fence is filled with snow, while drifts cast by the vertical-slat, "Canadian" snow fence extend downwind about 26.5 times fence height (Tabler 1980).

The study conclusively demonstrates that wildlife depredation can be as severe a problem to shelterbelts planted on rangelands as severe climatic conditions. Siberian elm and oldman wormwood are not suitable species if white-tailed jackrabbits and Richardson's ground squirrels, respectively, are present. Different mammal species at another shelterbelt location might prohibit use of some tree or shrub species that were acceptable in this study. Indeed, woody-species plantings on two mine spoils north of Interstate-80 in southcentral Wyoming were also subjected to severe wildlife depredation (Howard et al. 1979).

An inventory of mammals indigenous to a prospective shelterbelt location should precede establishment of the planting, and plant species attractive to wildlife should not be planted. Various types of repellents and shields are available to protect plants from wildlife. Use of these agents may alleviate depredation during establishment. However, shelterbelts adjacent to rangeland will be subjected to wildlife depredation over the life of the planting. This fact must be recognized and accounted for in project design.

Introduction

Scientifically designed snow fence systems along Interstate-80 in southcentral Wyoming have improved the safety of motorists during periods of blowing snow and have reduced winter maintenance expenditures (Tabler and Furnish 1982). Fence systems consist of wooden structures 3.8 m in height, with lesser use of barriers 3.2 m or 2.6 m tall. Multiple rows of fences are necessary in locations with high snow transport. While the value and efficiency of snow fences in trapping blowing snow is unquestionable, questions have arisen whether shelterbelts might also serve the same snow control function. Shelterbelts also may be less of an aesthetic intrusion on the landscape than are wooden snow fences.

The ability of shelterbelts to reduce windspeed and enhance the beauty of farmsteads on the edge of the Great Plains in eastern Wyoming (where elevations range from approximately 1,250 m to 1,850 m) is well accepted. Technical information exists concerning the suitability of various tree and shrub species as well as proven methods to establish and care for the planting (Howard 1982, Johnson and Anderson 1980, Cook 1978, Howard 1964, Edmondson 1951). The climate further west in the state on the high plains traversed by Interstate-80 is too severe for intensive agriculture, and the land retains native shortgrass or sagebrush vegeta-

tion. Information is lacking about the ability of shelterbelt species to survive and grow under the severe environmental conditions that exist along the Interstate where elevations reach 2,400 m. Such information though, is essential for assessing the possible use of shelterbelts for highway snow control.

The current study was initiated in cooperation with the Wyoming State Highway Department to determine (a) if shelterbelt species can be established in windswept locations typical of high-elevation rangeland traversed by Interstate-80 in southcentral Wyoming, (b) if placement of the planting downwind of a snow fence to take advantage of the reduction in windspeed enhances plant survival and growth, and (c) the survival and growth characteristics of species for a 5-year period after planting.

An existing snow fence system on the south side of Interstate-80 about 8 km east of the town of Elk Mountain was utilized as a study site (fig. 1). The site is in rolling terrain at a 2,300-m elevation and consists of a lead fence 3.2 m tall and downwind fence 3.8 m tall. Native vegetation was dominated by Wyoming big sagebrush (*Artemisia tridentata* sub. *wyomingensis*) about 10 cm tall. Soil belonged to the Lithic Cryoboroll great soil subgroup and developed in place from outwash material originating in the nearby Medicine Bow Mountains. The solum was 30 cm thick with a sandy loam texture in A and B horizons.

The planting site is 35 by 152 m and fenced with woven wire on three sides. The 3.8-m snow fence on the downwind boundary enclosed the remaining side to exclude grazing by livestock and big game. Windspeeds over about 60% of the site were ameliorated by the 3.2-m upwind snow fence; the remainder of the site was fully exposed to ambient winds. The site was plowed to kill all native vegetation at study initiation in 1975 and sprayed with a herbicide in 1976 to control weed invasion. Weeds around plants were subsequently controlled mechanically one time so that competition from native vegetation had little, if any, effect on stud results. The planting remained insect-free throughou the study.

Figure 1.—The shelterbelt study site was on the windward side of the 3.8-m snow fence nearest Interstate-80 at the bottom of the photo. Windspeed over 60% of the study site was reduced by an upwind snow fence 3.2 m tall.

Three conifer species, Colorado blue spruce (*Pice pungens*), ponderosa pine (*Pinus ponderosa*), and whi fir (*Abies concolor*), and three deciduous species, Ru sian olive (*Elaeagnus angustifolia*), Siberian elm (*Ulmu pumila*), and Siberian peashrub (*Caragana arborescens* were evaluated. These species are considered drough resistant and adapted for use within the Central Gre Plains region of Wyoming (Howard 1982). The stoc was obtained from the Fort Collins nursery of the Co orado State Forest Service, except for Siberia peashrub, which was dug from an existing shelterbe near Cheyenne, Wyo. The planting was made June 2 and 28, 1975. Plants were placed in holes 61 cm i diameter in which soil was previously loosened to 61-cm depth with an auger.

Conifers were 10-15 cm tall when planted and cam from container-grown stock, while deciduous specie were planted as bare-root stock. Bare-root stock wa held in cold storage for about 6 weeks after digging un til the field site had been prepared. Two slow-releas fertilizer tablets (20% nitrogen, 10% phosphorus, 5% potassium) that weighed about 20 g each were placed i soil adjacent to each plant at the time of planting. Th plants were watered in the summer months during 197 and 1976 at irregular intervals so that soil moistur stress was not a survival factor. Most individuals tha died in the first year of study were replaced in Jun 1976 with new stock obtained from the same source a that planted in 1975. Consequently, stud measurements for the 1976 planting ended 1 year late than for the 1975 planting to permit expressing all dat in terms of years after planting.

Each species was planted in a single row 122 m lon oriented perpendicular to the southwesterly prevailin winds, except for Siberian peashrub, which wa planted in two rows (fig. 2). About 60% of each row wa within that portion of the study site protected by the up wind snow fence. The remainder of each row was ex posed to prevailing winds. The location of each row o plants with respect to the snow fence 3.2 m tall on th upwind side of the planting site is shown on figure 2 the distance between plants is also shown on the figure

In addition to the six conventional shelterbelt tre and shrub species, two common western shrubs and a sagebrush introduced from Europe were evaluated. These were chosen because of rapid growth characteristics exhibited at the Ephraim, Utah, shrub garden maintained by the Intermountain Forest and Range Experiment Station. Two sources of basin big sagebrush (*A. t. sub. tridentata*) collected in Colorado and Nevada, white rabbitbrush (*Chrysothamnus nauseous sub. albicaulis*), and oldman wormwood (*A. abrotanum*), were planted. Oldman wormwood is a deciduous, European shrub that grows from 1.0 m to 1.5 m tall (Plummer 1974). Because of its ability to withstand drought, oldman wormwood is used as an ornamental and to vegetate disturbed sites, such as roadside cut or fill slopes.

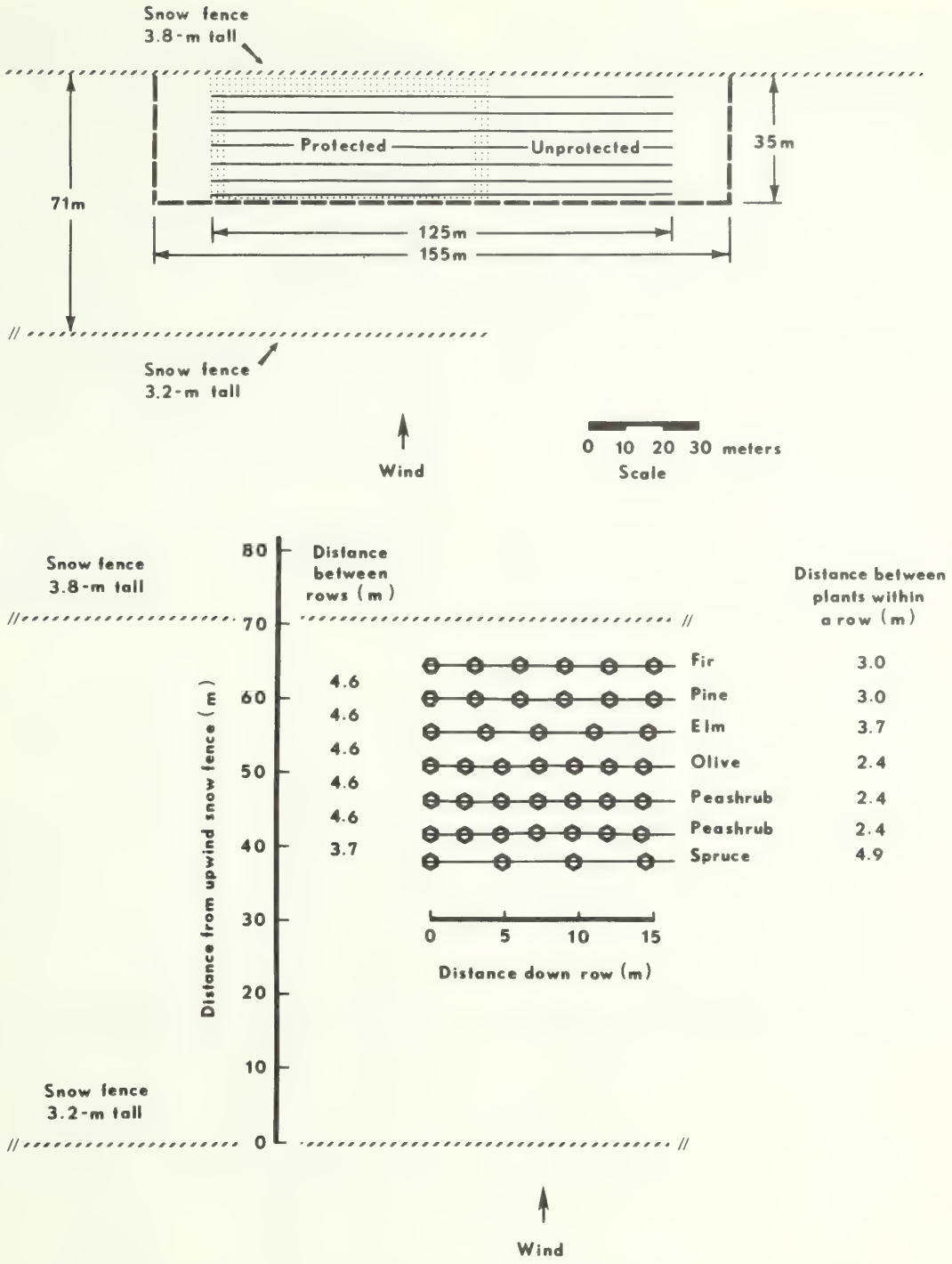


Figure 2.—Location of the upwind snow fence 3.2 m tall and the 3.8-m snow fence with respect to the planting site is shown on the top half of the figure. The location of each row of species at the study site, spacing between rows of plants, and spacing between plants within a row, is shown on the bottom half of the figure.

Big sagebrush and white rabbitbrush seedlings were ug at the Ephraim shrub garden May 11, 1976. Rooted nd unrooted oldman wormwood cuttings were obtain- l from stock at the shrub garden, and all species were anted 2 or 3 days later at the shelterbelt site. angeland shrubs were placed 0.5 m on either side of e rows of Colorado blue spruce and ponderosa pine. Individuals of the three rangeland shrubs were planted sequentially at 0.8 m intervals until 28 plants of each species had been placed on either side of a conifer row. Rangeland shrub rows were 63.3 m long. Rooted oldman cuttings were placed adjacent to the Colorado blue spruce row, and unrooted cuttings were placed adjacent to the ponderosa pine row. Half of the plants of

the Colorado and Nevada selections of big sagebrush were placed along the Colorado blue spruce row, and half were placed along the ponderosa pine row. The configuration of the rangeland shrub planting did not allow the influence of snow fence protection upon plant establishment and growth to be evaluated.

Plant survival was determined in the spring as growth commenced (early June) and in the fall (early October) at the close of the growing season. Beginning in 1978, plant height was measured in the fall, and permanently marked plants of each species were photographed. The cross-sectional area and density of snow in the drift cast by the upwind snow fence were measured in March at the time of maximum accumulation.

Climate

Temperature and precipitation records collected in Elk Mountain at a National Oceanic and Atmospheric Administration (NOAA) co-operator station are available for the study period. Summer precipitation was measured at the shelterbelt site in a storage gage from 1977 to 1979 (after supplemental watering wa discontinued). The orifice of the gage was located a ground level to minimize the influence of wind on gag catch. In 1976, wind speed was monitored at a 2-r height 12.6 km northwest of the planting site. Averag monthly wind speeds measured at this gage are believec representative of values existing at the study site.

The shelterbelt site is typical of high platea rangeland in Wyoming. Long-term annual precipitatio at Elk Mountain is 32.7 cm, while the 5-year averag during the study was 33.1 cm. Individual years range from 27.7 cm to 38.6 cm. Nearly a third of the yearl total, 12.7 cm per year for the 5-year study interval, fel during the snow drifting season, which extends fron November 1, to March 31 (fig. 3). Summer precipitatio measured at the shelterbelt site averaged 8.3 cm for the June-September interval (table 1).

The growing season extended from late in May, whe deciduous species leafed out, until September, when freezing night-time temperatures and a shorter day length caused leaf-fall. Night-time temperatures were consistently above freezing only in July and August Minimum monthly air temperatures were below freez

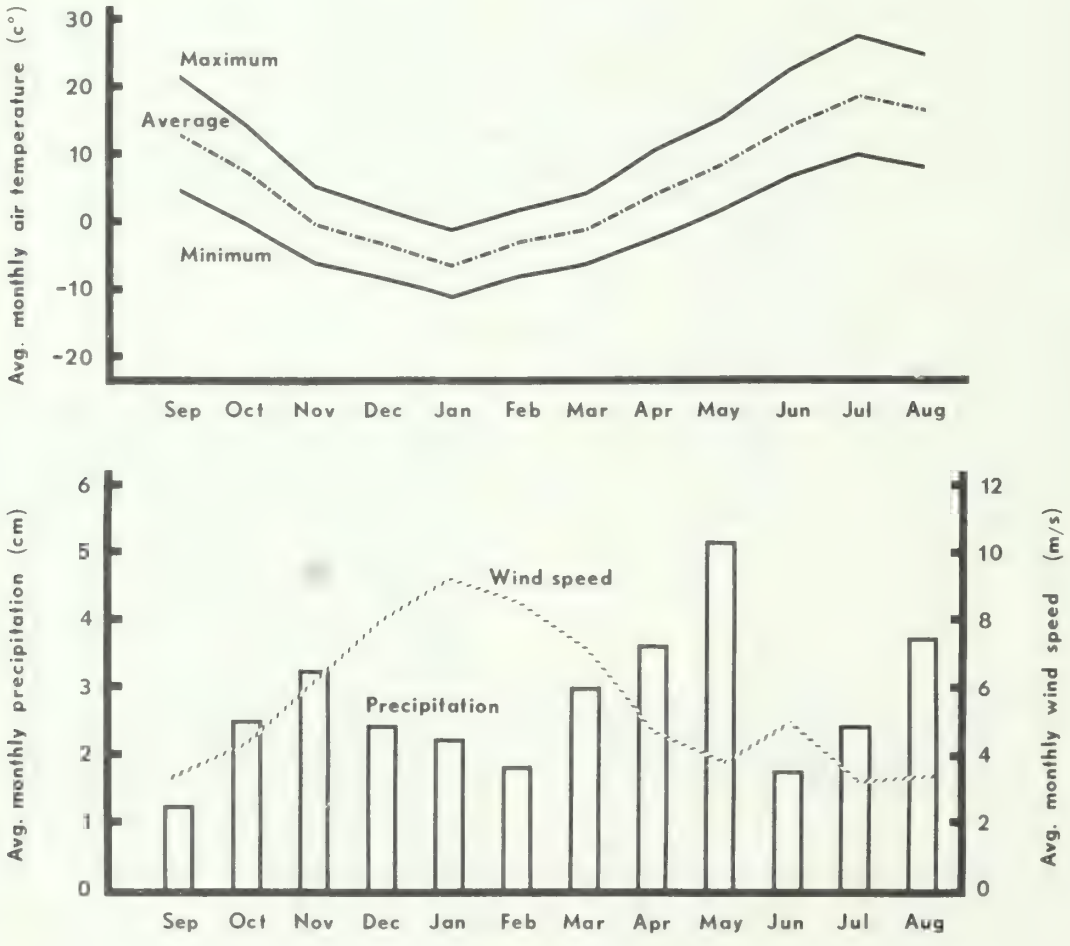


Figure 3.—Average monthly air temperature (top) and precipitation in the town of Elk Mountain and wind speeds during 1976 (bottom) as measured 12.6 km northwest of the study site.

Table 1. — Summer precipitation (cm) at the shelterbelt site

Year	Month				Total
	June	July	August	September	
1977	0.4	3.5	5.8	0.1	9.8
1978	1.1	1.3	3.8	Snow[a]	6.2
1979	1.4	1.3	5.2	.7	8.6
Average	1.0	2.0	4.9	.4	8.3

[a]*No measurement because of drifting snow; 2.5 cm precipitation was recorded during September at the National Oceanic and Atmospheric Administration co-operator station at Elk Mountain.*

ng from October through April (fig. 3). Monthly maximum air temperature peaked in July at 27° C. The yclic yearly temperature and wind regimes are about 6 nonths out of phase (fig. 3). Windspeeds are at a maximum in midwinter and averaged more than 6 m/s hroughout the 5-month drifting season. Monthly peeds were lowest in July and August with a value of bout 3 m/s. Consequently, the simultaneous occurence of low air temperature, frozen soil, and high vind speeds, created severe desiccation stresses on lants in winter months.

Results and Discussion

Effects of Wind Protection on Plant Establishment and Growth

The difference in survival of the six commonly lanted shelterbelt species between locations protected nd unprotected by the upwind snow fence was tested r significance by Chi Square. The difference in survival attributable to location was not significant = 0.05) 1 and 2 years after planting for any species.

The influence of fence protection on growth of the six elterbelt species was evaluated after three, four, and ve growing seasons, utilizing a *t*-test. The only signifint height difference was for Siberian elm in the fifth owing season as elms growing in the unprotected cation were taller than elms growing downwind of e snow fence. However, browsing by white-tailed ck rabbits (*Lepus townsendii*), not fence protection, as the primary factor influencing elm height at this ne. The average height of elms progressively decreasl after the third growing season because of jack rabbit epredation.

The configuration of snow fences at the study site mplicated interpretation of study results in several ays, but should not have altered the basic outcome of e study. The rows of plants extended across the nced/unfenced boundary. Wind is not always perpenicular to the fence which effects wind flow patterns d snow accumulation near the fence end. For exame, overwinter snow accumulation is reduced for a stance of 12 times fence height from the end of a nce (Tabler 1980). Consequently, plants adjacent to e fenced/unfenced boundary received somewhat less an full protection from the wind in the protected location and some protection from the wind in the unprotected location.

There was insufficient space between snow fences to locate the planting downwind of the equilibrium lee drift cast by the 3.2-m snow fence. At maximum storage capacity, the drift cast by a Wyoming snow fence extends 29.5H (H is vertical height of the fence) downwind from the fence and the deepest part of the drift is 6.7 H downwind from the fence (Tabler 1980). The planting was located between 12H and 20H downwind of the lead snow fence. The snow drift cast by the lead fence completely covered the planting at the close of the 1978-1979 and 1979-1980 winters, but failed to reach any part of the planting in the drought winters of 1976-1977 and 1980-1981 (fig. 4). Plants were in a uniform temperature regime at slightly below 0° C when covered by snow and were completely protected from wind. Approximately 250 cm of snow covered Colorado blue spruce in the two heavy winters; snow depth decreased across the planting site and the row of white fir was covered by 100 cm of snow. Some damage to Colorado blue spruce and Siberian peashrub did result from snow settlement.

The snow fence 3.8 m tall enclosing the downwind side of the study site reduced wind speeds immediately in front of the fence. The upwind drift could have extended beyond the row of Colorado blue spruce had this fence reached maximum storage capacity. However, the upwind drift was small even in heavy winters and barely reached the row of white fir which was closest to the fence. It is assumed then, that the presence of the 3.8-m fence had a negligible effect on wind speeds in the planting zone.

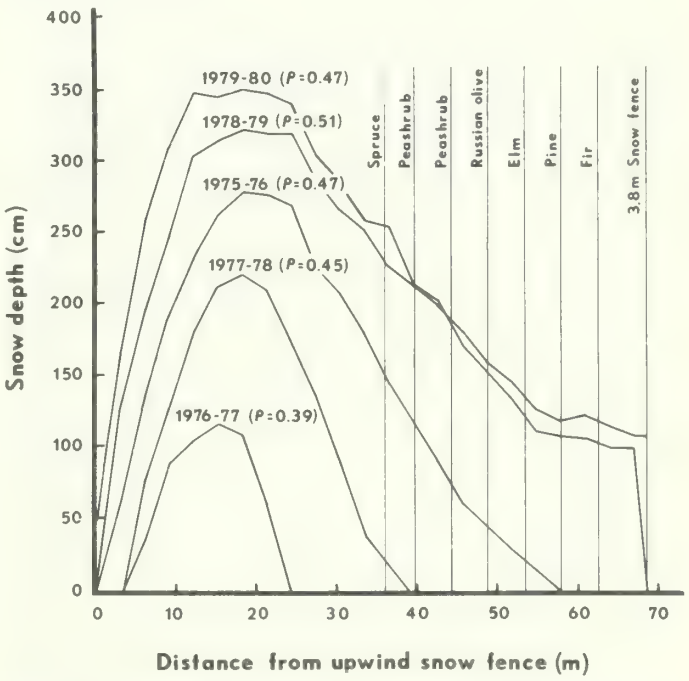


Figure 4.—Cross-sectional area and density (ρ) of snow in the drift cast by the 3.2-m upwind snow fence at maximum accumulation. The location of each species with respect to the upwind fence is indicated on the figure.

Species Survival and Growth

Because results of the protected-unprotected tests indicated that survival and growth of shelterbelt species were not affected by microclimatic changes induced by the upwind snow fence, data from the two locations were combined to determine a species average. Most mortality occurred within 2 years of planting (table 2). Colorado blue spruce and white fir survival at the end of 5 years was the highest of any species, 94% and 84%, respectively. Only 65% of the ponderosa pine planted in 1975 survived for 5 years, but 93% of the 15 pines planted 1976 survived, similar to the survival rate of other conifers. This suggests that either the stock or method of handling the stock in 1975 contributed to high ponderosa pine mortality.

The survival rate for Siberian elm 5 years after planting was 65%, the best of any deciduous species (table 2). Russian olive's mortality exceeded that of other deciduous species: only 16% of individual plants were alive after 5 years. However, all Russian olive mortality occurred within 2 years of planting and most plants died in the winter indicating a lack of winter-hardiness to conditions at the study site. Siberian peashrub losses also occurred in the first 2 years after planting.

Basin big sagebrush was the only species to experience appreciable mortality beyond the second year from environmental stresses (table 2). Both Colorado and Nevada selections of basin big sagebrush were poorly adapted to the severity of winter conditions at the planting site. Individual plants often suffered varying degrees of canopy dieback during the winter, even when they were not completely killed.

Shelterbelt plantings must not only establish readily, but also grow rapidly after establishment, to be a viable alternative to snow fences. Depredation by small mammals severely limited both establishment and growth of oldman wormwood and growth of Siberian elm. Growth of white rabbitbrush was moderately affected. Average height of all species three, four, and five growing seasons after planting is shown in figure 5.

Only 38% of unrooted oldman wormwood cuttings were alive by fall the year of planting, while 86% of rooted cuttings survived the summer. The difference is primarily attributable to browsing by Richardson's ground squirrels (*Spermophilus richardsonii*) which are active from April until early August, the major portion of the growing season. Wire cages, 46 cm long and 10 cm in diameter, were placed around individual oldman plants in late July the year they were planted, when it was discovered how palatable herbage was to ground squirrels. Unrooted oldman cuttings apparently had insufficient reserves to withstand repeated browsing while simultaneously establishing a root system. Foliage within the cages was protected from ground squirrels, but growth protruding from the side or top of the cage was quickly eaten. The cages remained around plants that originated from unrooted cuttings throughout the study, and plant height was similar to cage height each fall (fig. 5).

The row containing rooted oldman wormwood cuttings was fenced in June 1978 to exclude Richardson's ground squirrels to permit determining the growth potential of oldman at the study site. Fencing had a 6-mm-square mesh, and extended 41 cm above the soil surface and 10 cm below the surface; a lip of wire extended outward from the bottom of the fence 10 cm to discourage ground squirrels from burrowing directly under the fence. Two electrified wires, spaced 5 cm apart, were placed above the fence. Fencing was moderately successful the summer of installation, and oldman increased to an average height of 69 cm from 41 cm the previous summer when plants were protected by wire cages. A sufficient number of squirrels burrowed under the fence the following summer to heavily browse plants and reduce height to 23 cm and to 13 cm the following year (fig. 5). The cumulative effects of heavy browsing by Richardson's ground squirrels

Table 2 —Number of individuals of each species that were planted and survival percentages at the end of each summer and year subsequent to planting

Group / Species	Number planted			Survival									
				First year		Second year		Third year		Fourth year		Fifth year	
	1975	1976	Total	Summer	Year	Summer	Year	Summer	Year	Summer	Year	Summer	Year
Conifer													
Blue spruce	25	10	35	100	100	97	94	94	94	94	94	94	94
Ponderosa pine	40	15	55	82	78	76	75	75	75	73	73	73	73
White fir	41	10	51	100	90	86	84	84	84	84	84	84	84
Deciduous													
Russian olive	51	10	61	89	39	33	16	16	16	16	16	16	16
Siberian elm	34	0	34	82	76	74	71	71	71	71	71	71	65
Siberian peashrub	101	11	112	76	76	62	55	54	54	54	54	54	54
Rangeland shrub													
Basin big sagebrush													
Colorado source	0	56	56	41	38	36	32	32	27	21	11	11	11
Nevada source	0	56	56	50	38	38	38	38	30	27	25	25	25
Oldman wormwood													
Rooted cutting	0	56	56	86	84	84	84	84	84	80	79	50	32
Unrooted cutting	0	56	56	38	32	32	32	32	32	32	32	32	32
White rabbitbrush	0	112	112	23	20	20	20	20	20	20	20	20	20

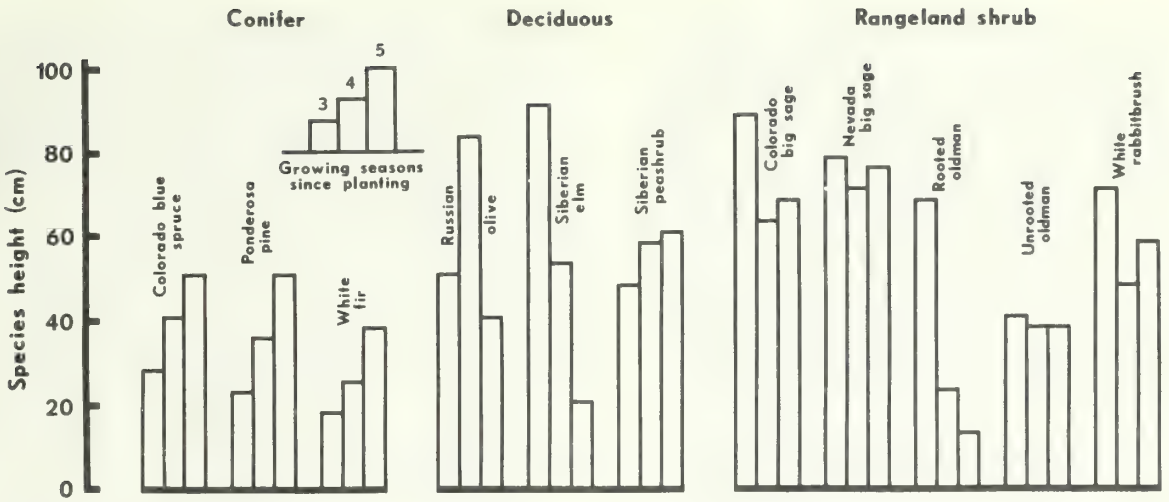


Figure 5.—Average height of species at the end of the third, fourth, and fifth growing seasons after planting.

duced survival from 84% to 32% between the third d fifth year after planting.

Richardson's ground squirrels browsed white rabbit-ush in the summer and its stems and branches were so clipped in the winter by white-tailed jack rabbits, t this use did not cause any mortality. However, berian elms were severely damaged by jack rabbits ring the winter. Rabbits clipped twigs within reach d debarked the trunk, thus girdling the tree and kill-g top growth. Elms decreased in height after the third owing season because of the depredation. All elms at e study site had a prostrate growth from 5 years after anting, and they will not become trees unless pro-cted from jack rabbits.

The sharp decrease in height of Russian olive the fifth owing season (fig. 5) illustrates that shelterbelts are bject to man-induced calamities as well as those from matic or biological sources. Thistles growing along a unty road a short distance upwind from the study site ere sprayed with 2,4-D in June 1979. Sufficient her-cide drifted across the study site to kill the tops of all ssian olives. Plants resprouted later in the summer, t by fall average height was only about half that of the eceding year. Rabbitbrush was also damaged by her-cide drift.

Observations About Individual Species

Colorado blue spruce (fig. 6). — The terminal buds of ruce were damaged more severely than other con-rs the winter after planting, probably from wind-duced desiccation. A short wooden shield was placed the windward side of each spruce prior to the se-nd winter. Some plants were damaged in subsequent ars after trees extended above the shield, but damage as not as extensive as the winter after planting. Mean ight was 51 cm at the close of study, with a max-um height of 81 cm.

Ponderosa pine (fig. 7). — The growth rate of pine in-eased each year, and average height equaled that of ruce at the close of study. The leaders of many pines developed a distinct crook in 1979, caused by 2,4-D which drifted across the planting site when roadside weeds were sprayed.

White fir (fig. 8). — The initial rate of height growth was the slowest of any conifer, but increased to 13 cm the fifth growing season, about the same as for other conifers. Plants were slow in recovering from damage to the terminal bud suffered the winter after planting and are developing a bushy growth form.

Russian olive (fig. 9). — Mortality was confined to the first 2 years following planting, but was the highest of any traditional shelterbelt species. Those plants that did survive grew rapidly and were 84 cm tall after four growing seasons. During the following year, the tops of plants were killed by 2,4-D drift, and average height decreased about 50%. The lateral crown spread of Russian olive was about equal to plant height, so that this shrub forms an effective barrier to trap drifting snow.

Siberian elm (fig. 10). — Elms established quickly and averaged 91 cm in height three growing seasons after planting with a maximum height of 183 cm. Height progressively decreased in subsequent years because of jack rabbit depredation during the winter. No elm regained a tree-like form once the trunk was girdled, and it is doubtful this species can survive at the study site because of the severity of jack rabbit depredation.

Siberian peashrub (fig. 11). — Peashrubs were 48 cm tall three growing seasons after planting, but little additional height growth occurred the following 2 years. Individual plants remained spindly, and this species would require close spacing to form an effective wind barrier at the study site.

Basin big sagebrush (fig. 12). — Basin big sagebrush established quickly and the Colorado and Nevada selections were 69 cm and 58 cm tall, respectively, at the end of the second growing season. Neither selection was physiologically adapted to the harsh, windy environment at the planting site. Mortality occurred throughout the study and was particularly heavy after the severe 1978-1979 and 1979-1980 winters.

Oldman wormwood (fig. 13). — The extremely palatable nature of oldman wormwood foliage to Richardson's ground squirrels prohibits its use at locations where this species of ground squirrel is present. The row containing oldman cuttings initially rooted was fenced to exclude Richardson's ground squirrels before the third growing season and plants were 69 cm tall by fall. Squirrels tunneled under the fence the next summer and height decreased to 23 cm. Continued heavy browsing in subsequent years reduced plant vigor to such a low state that 47% of the original population of rooted oldman died the fifth year after planting.

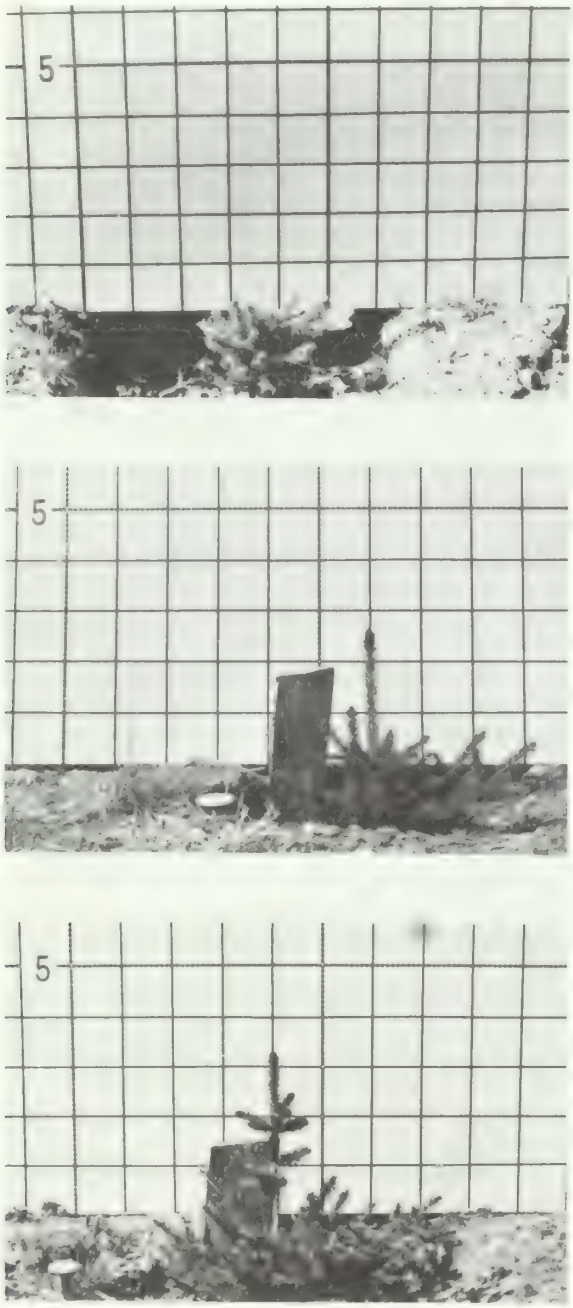


Figure 6.—Growth form of a Colorado blue spruce three (top), four (middle), and five (bottom) growing seasons after planting. The grid is composed of 1-dm squares.

White rabbitbrush (fig. 14). — White rabbitbrus was the only rangeland species to show promise for u in a shelterbelt planting. It was browsed b Richardson's ground squirrels in summer and whit tailed jack rabbits in winter, though not heavily enoug to produce mortality. Plants grew rapidly and average 61 cm in height at the end of the second growin season. They fluctuated around this height for the re mainder of the study. Only 20% of plants survived year after planting, but there was no additional mortal ty. Additional field trials are needed to improv establishment methods before this species can b recommended for shelterbelt use.

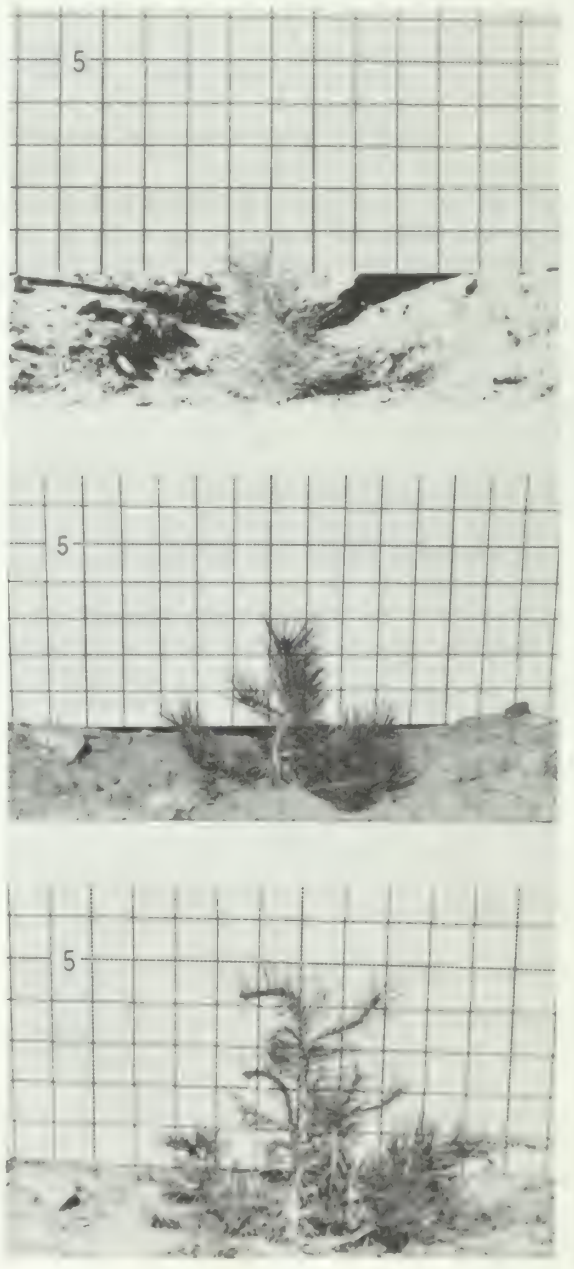
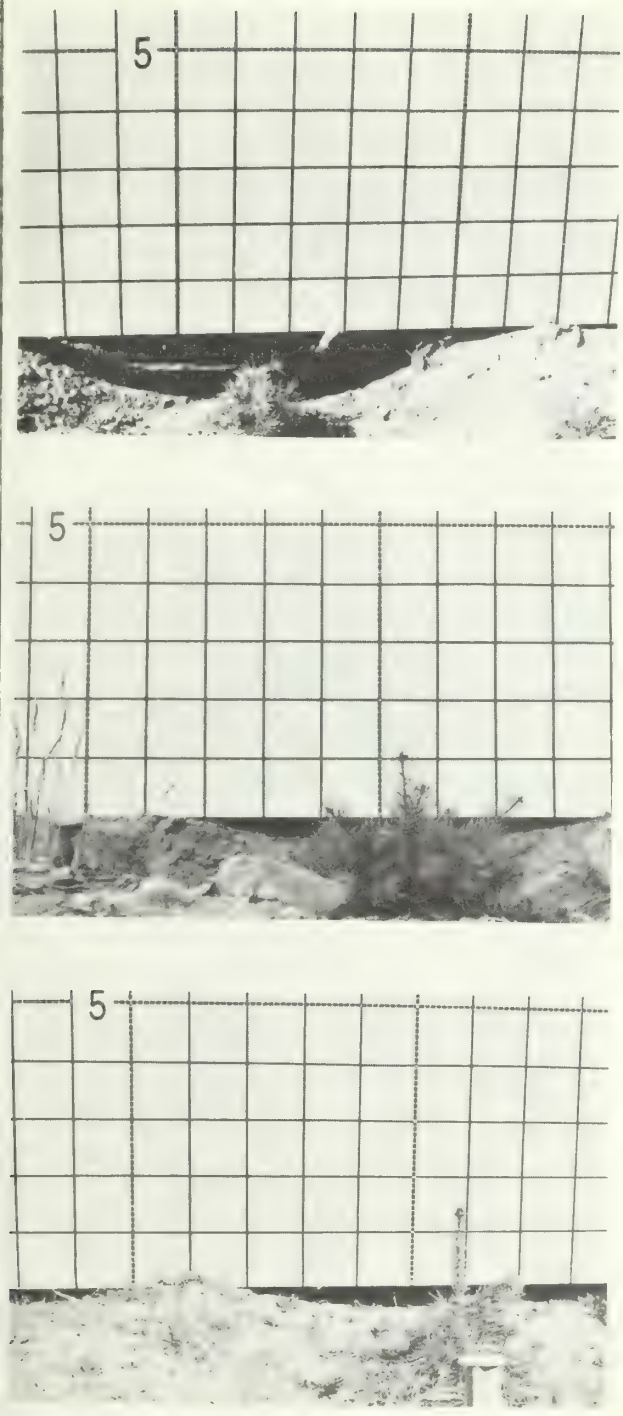


Figure 7.—Growth form of a ponderosa pine three (top), four (middle), and five (bottom) growing seasons after planting. Contorted leader growth in bottom photo was caused by 2,4-D which drifted across the study site when roadside weeds were sprayed. The grid is composed of 1-dm squares.



ıre 8.—Growth form of a white fir three (top), four (middle), and ve (bottom) growing seasons after planting. The grid is composed f 1-dm squares.

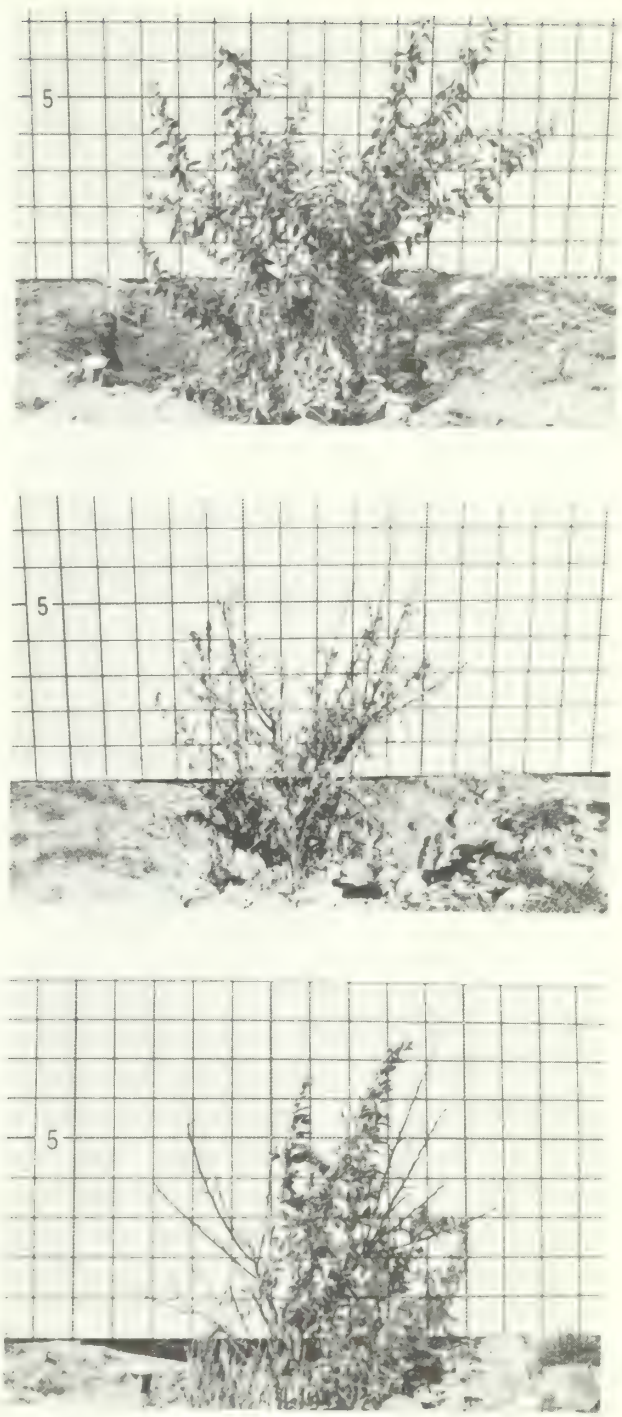


Figure 9.—Growth form of a Russian olive three (top), four (middle), and five (bottom) growing seasons after planting, Top growth was killed (bottom photo) by 2,4-D drift, but plants resprouted from the trunk later in the summer. The grid is composed of 1-dm squares.

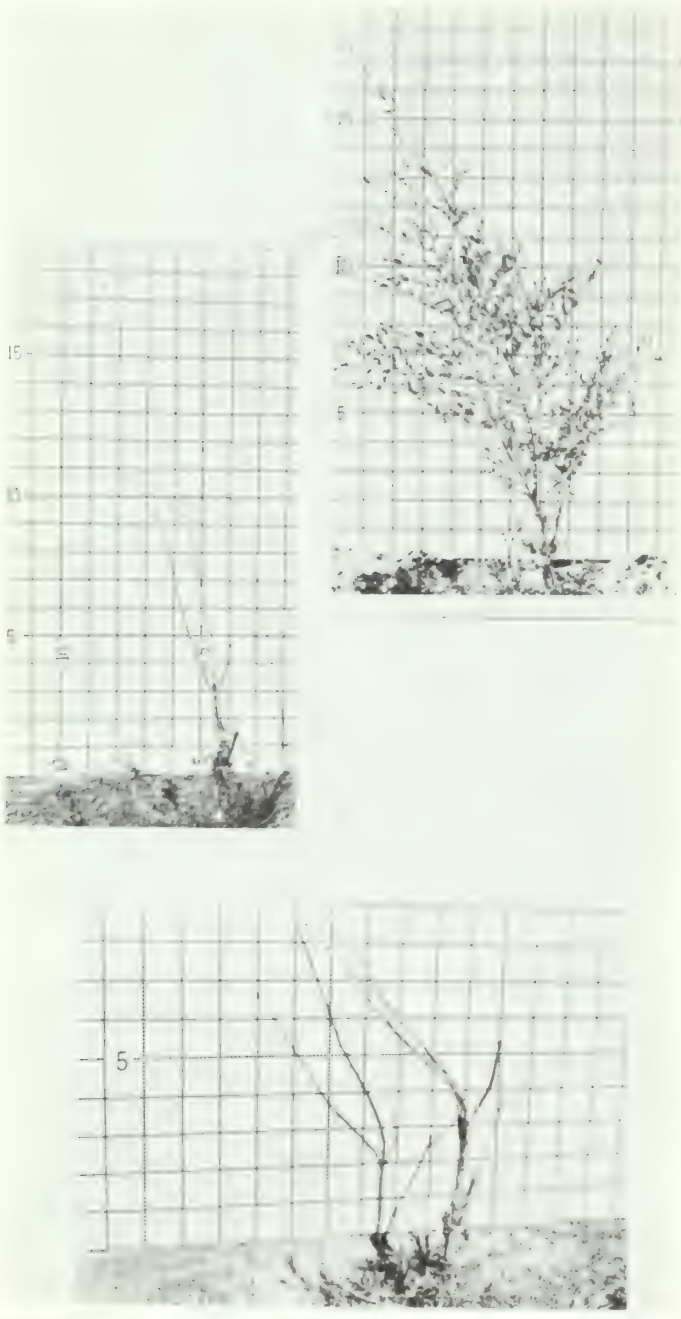


Figure 10.—Growth form of a Siberian elm three (top), four (middle), and five (bottom) growing seasons after planting. Jack rabbits girdled the trunk and browsed on twigs during winter months. The grid is composed of 1-dm squares.

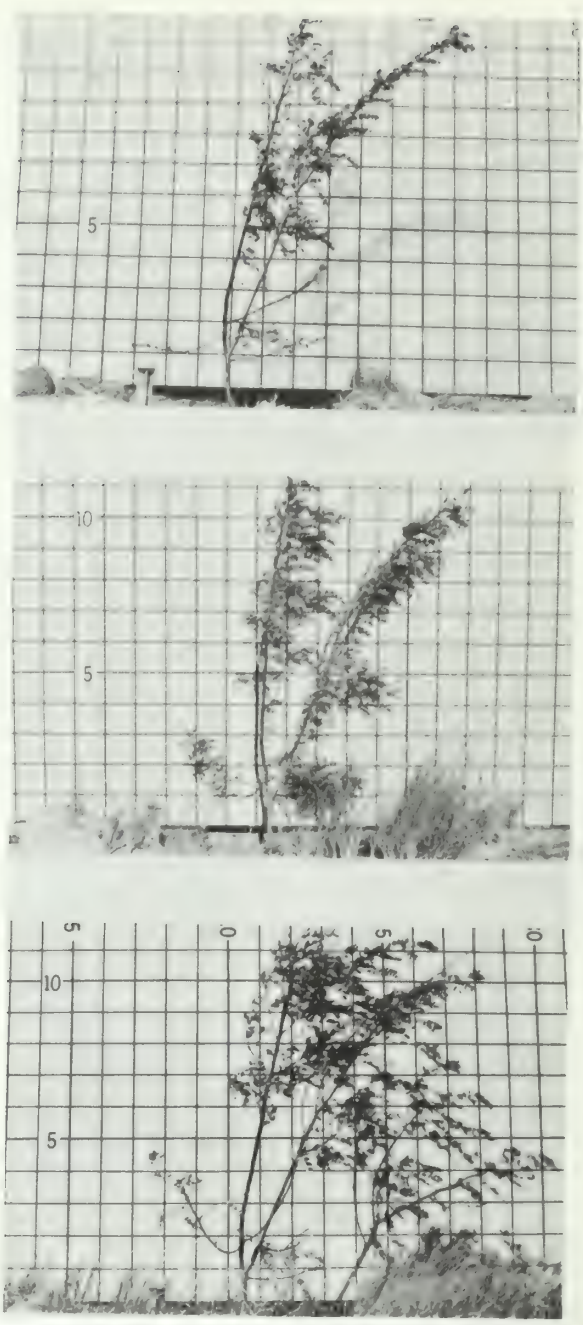


Figure 11.—Growth form of a Siberian peashrub three (top), four (middle), and five (bottom) growing seasons after planting. The grid is composed of 1-dm squares.

ıre 12.—Growth form of a basin big sagebrush from Colorado
ree (top), four (middle), and five (bottom) growing seasons after
anting. The selections from both Colorado and Nevada winter-
lled through the study. The grid is composed of 1-dm squares.

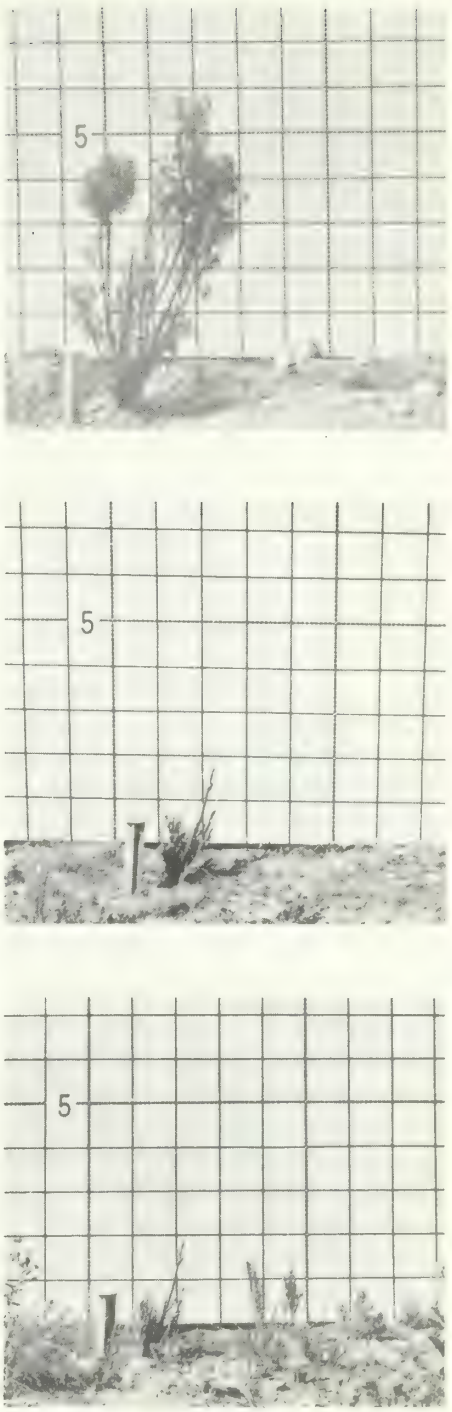


Figure 13.—Growth form of an oldman wormwood planted as a rooted cutting three (top), four (middle), and five (bottom) growing seasons after planting. The row was fenced to exclude Richardson's ground squirrels at the beginning of the third growing season, but depredation in the following two years was still severe. The grid is composed of 1-dm squares.

Figure 14.—Growth form of a white rabbitbrush three (top), four (middle), and five (bottom) growing seasons after planting. Rabbitbrush was moderately damaged by 2,4-D drift (middle photo). The grid is composed of 1-dm squares.

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Lubbock, Texas
Rapid City, South Dakota
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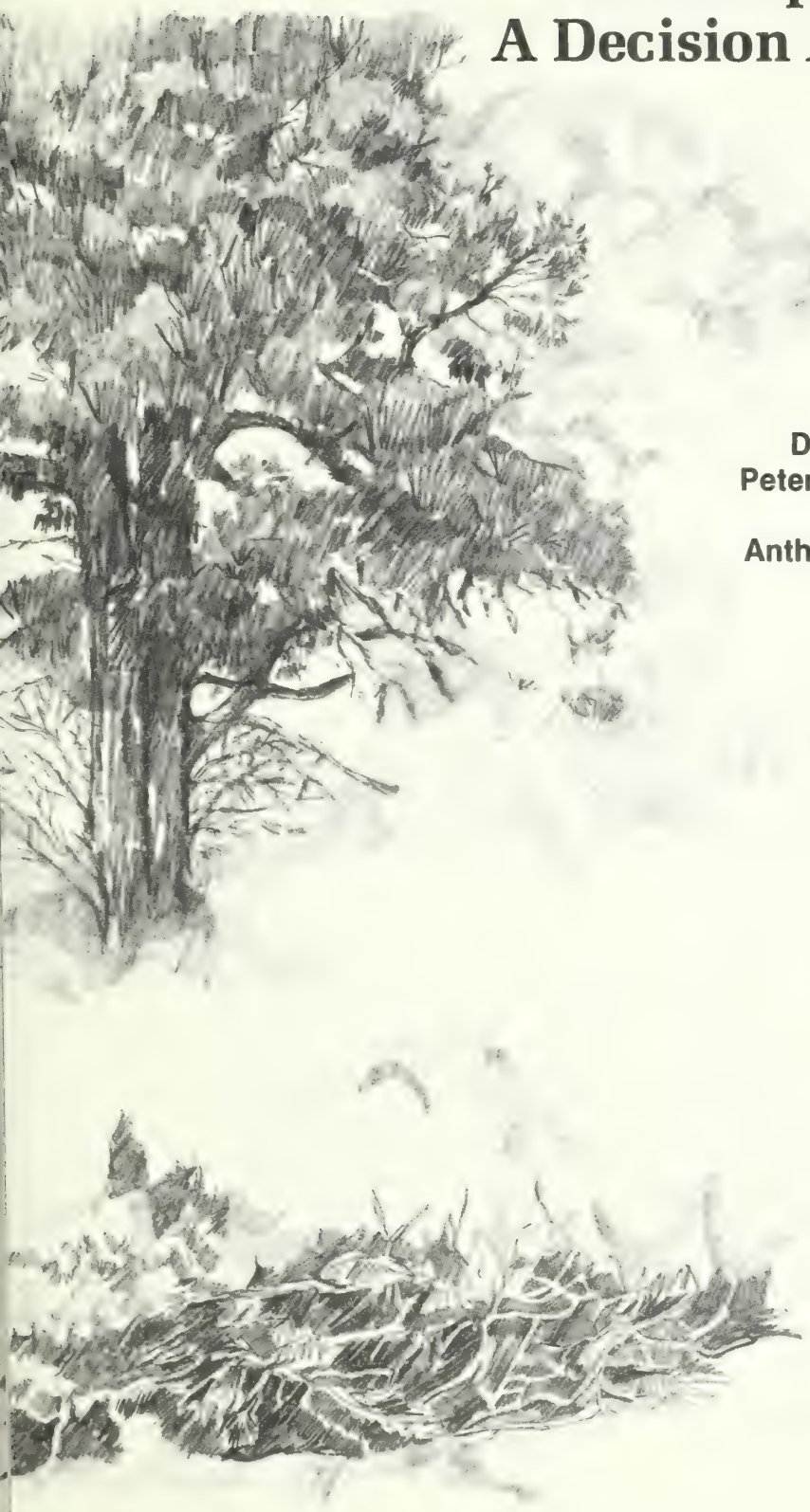
The Escaped Fire Situation: A Decision Analysis Approach



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Research Paper RM-244
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

USDA Forest Service
Research Paper RM-244

February 198

The Escaped Fire Situation: A Decision Analysis Approach[1]

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Abstract

A preliminary decision analysis model addressing the choice among alternative suppression strategies on escaped wildfires is presented. A case study application of the model, in the context of an Escaped Fire Situation Analysis on the Wallowa-Whitman National Forest, is described and discussed.

Acknowledgments

The authors thank Al Oard, Forest Supervisor of the Wallowa-Whitman National Forest, for his cooperation, and the staff of the Wallowa-Whitman National Forest, particularly Dave Anderson, Gordon Foster, Dick Mangan, and Bruce McMillan, who provided much of the information used in the research and generally provided helpful suggestions and guidance in our effort. Assistance with the development and implementation of computer software was provided by Richard F. Yancik and James J. Allen; William G. Stillwell assisted with various analyses.

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The Escaped Fire Situation: A Decision Analysis Approach

David A. Seaver, Peter J. Roussopoulos, and Anthony N. S. Freeling

Management Implications

Only about 5% of all wildland fires in the United ates escape initial suppression efforts and become oject fires, but these escaped fires account for ughly 95% of all wildfire-related costs and damages. a result, Forest Service fire management policy lls for a careful analysis of all escaped wildfires in eal-time," to ensure that each fire is managed in the ost efficient manner feasible.

Although the escaped fire policy has been in effect ace 1978, current direction for the prescribed proc- s is often too time-consuming and cumbersome for e in real-time emergency decisionmaking. Explicit eans are not available for making tradeoffs among nflicting decision criteria, and there is no clear echanism for crosswalking the analysis with broader source management plans and programs. The result that often one of the following two situations occurs: The results of the hurried and incomplete analysis e rejected because they are counter-intuitive, thus wasting the time and effort devoted to the analysis; or (2) the analysis results are accepted and followed, but the necessarily incomplete nature of the analysis results in an inefficiently handled fire.

This report describes an initial study to determine the basic structure of escaped fire strategy decisions in terms of reasonable alternatives, appropriate decision criteria, and critical information uncertainties. It further investigates the use of concepts and methods of decision analysis to model these decisions and to identify crucial aspects of the decisions that need to be addressed explicitly, and aspects that are less crucial, where effort can be saved to improve analytical efficiency.

Results of this initial study suggest that decision analysis methods, together with concepts of multiattribute utility theory, can provide a consistent and logical framework within which to evaluate alternative suppression strategies on escaped wildfires. Additional research is needed, however, to explore possibilities for simplifying the model and reducing the number of value assessments required before the approach can be operationally useful in real-time.

Introduction

Current USDA Forest Service policy requires that ppression action on individual escaped wildfires be sed on a formal analysis of alternative strategies— Escaped Fire Situation Analysis (EFSA). Through EFSA, a preferred suppression strategy is to be ected on the basis of expected costs plus net ource value changes (C + NVC), with additional con- eration of social, environmental, and political fac- s. Thus, the EFSA decision is characterized by leoffs among the effects of fire on various resources swell as social, environmental, and political effects l fire suppression costs.

ecause the EFSA decision is made after a fire has aped initial attack efforts, it must be made rapidly, h little time for extensive analysis. It must also be le in the face of considerable uncertainty concerning rtant factors such as weather, fuels, topography, behavior, and the effectiveness of alternative sup- ssion strategies. Information that is relevant to the ision comes from many sources: meteorologists, fire avior officers, resource advisors, and fire suppres- specialists. These considerations suggest that deci- analysis (Brown et al. 1974, Howard 1968, Raiffa 8) may be an appropriate aid for the EFSA.

Decision analysis has been applied to several other problems in wildland fire management. For example, Hirsch et al. (1979, 1981) applied decision analysis to guide the selection of an activity fuel treatment. Other studies have used decision analysis to determine the value of fire-related information in forest planning (Seaver et al.)[4] and the value of improved fuels and fire behavior information for fire budgeting and fuel treatment decisions (Barrager et al. 1982).

This paper describes an analytic approach that embraces the most important uncertainties associated with operational EFSA decisions. A retrospective application of the approach to an escaped fire situation on the Wallowa-Whitman National Forest is also presented and discussed. Although the specific decision analysis model used in this case study is far too complex and unwieldy for practical application, the aggregate results of several detailed case analyses, such as the one discussed here, should provide valuable insights on the desirable features of a workable, operational model. Some of the study's preliminary implications regarding prospects for operational use of decision analysis models in real-time decisions are discussed herein.

[4]*Seaver, David A., Anthony N. S. Freeling, and Peter J. Roussopoulos. 1982. Value of fire-related information in forest planning. Decision Science Consortium, Inc., 7700 Leesburg Pike, Suite 421, Falls Church, Virginia. (In preparation).*

Analytic Approach

Decision analysis, the basic analytical approach used in this study, allows the evaluation of decision alternatives by breaking a complex problem into clearly defined components: alternatives, uncertain conditions or events, and outcomes. Various methods are used to quantify the uncertainties, in terms of probabilities, and the possible outcomes, in terms of value or desirability. To evaluate each alternative, the values assigned to its possible outcomes are weighted by their respective probabilities of occurrence and summed to yield the expected overall value for the alternative. If the analysis has adequately captured the key elements of the problem, the preferred alternative is the one with the highest expected value (i.e., lowest C + NVC).

A relatively simple example will clarify the basics of this approach and introduce some of the elements of the EFSA problem. Actually the EFSA involves two separate decisions: (1) whether or not a new EFSA is needed for a new work shift; and, if so, (2) what fire suppression strategy should be adopted. This analysis focuses on the latter decision—strategy selection—but it can provide some informal guidance with respect to the new EFSA decision as well. Figure 1 shows a simplified decision tree that represents a hypothetical strategy-selection decision. The various components of this example are discussed below.

Alternatives

The decision tree in figure 1 represents a choice between two fire suppression alternatives: A and B. The square (decision) node at the left of the figure denotes this choice. The lines or branches emanating from this node denote the two alternatives being considered.

In practice, alternative strategies must be defined on a case-by-case basis by appropriate fire and resource management experts. Strategies are specified in terms of the forces to be used, the equipment and material to be used, and locations of firelines. They must also incorporate knowledge about the availability of resources and other fire suppression activities. Appropriate suppression strategies on escaped wildfires

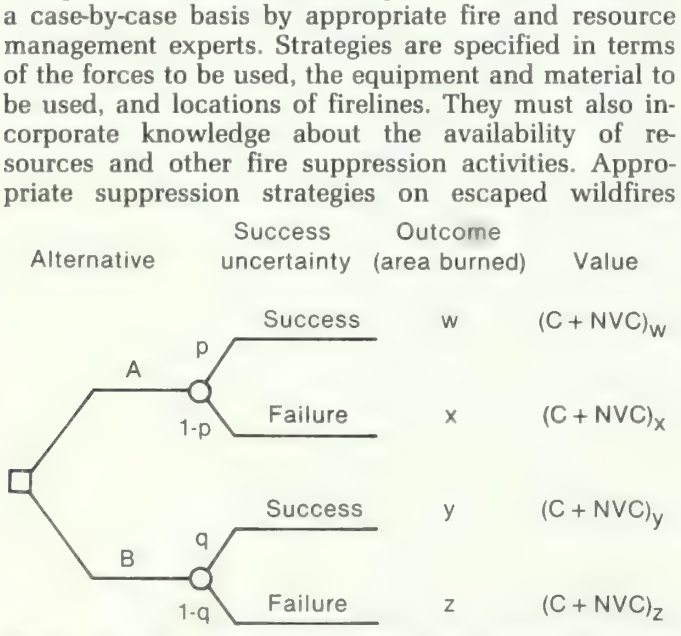

Figure 1.—Simple example of a decision tree for the Escaped Fire Situation Analysis.

include various levels of confinement, containmer and control. They may range from the use of smok jumpers, retardant tankers, helicopters, tracto pumpers, hand crews, and all other available r sources to control the fire at the smallest possible siz to simply confining the fire within some large, pred fined area, bounded by physical barriers to fi spread.

Uncertainties

The outcome of any choice between the suppressio alternatives will depend upon one or more uncerta events or conditions. In this illustrative case (fig. 1), primary uncertainty, shown by standard conventio with a circular node, is whether or not each of th alternatives (or either of them) will actually succeed stopping the fire. The likelihood of the uncertain eve (success) is quantified probabilistically using the be available information (the success probability is show as p for alternative A and as q for alternative B). Suc probabilities may be assessed using available data, e pert judgment, or additional modeling. In the EFS case study described subsequently, additional mode ing was found useful in estimating the probability success for each alternative.

Other uncertainties that influence the probability success for a suppression alternative include produ tion rates for assigned firefighting resources and fi behavior (rate of spread, intensity, occurrence severe phenomena such as spotting and crownin etc.). Furthermore, the probabilities of success for th alternative strategies may be differentially affected b these contributing uncertainties. For example, the su cess probability for a direct attack strategy may b reduced considerably more by more rapid fire sprea than that for an indirect attack. Thus, the simple mod in figure 1 could be expanded to include addition uncertain nodes that specify the probability of variou fire behaviors, incorporating success probabilities th are conditional on fire behavior.

Fire behavior, in turn, depends on additional unce tain factors; specifically, weather (wind speed an direction, temperature, humidity, atmospheric stab ity, fuel moisture, etc.), topography, and fuel cond tions. The model could be further expanded to explici ly include uncertain nodes and associated probabili distributions to account for these variables, makin fire behavior probabilities conditional on them. By ca cading conditional relationships in this manner, it often possible to separate highly difficult probabili assessments into several component assessments th can be made by simple, straightforward means. As th number of required assessments increases, howeve the task of the analyst grows commensurately.

Outcomes

Returning to figure 1, the outcome for each alte native (A and B) under each possible uncertain cond tion (success or failure) is expressed in terms of fin

re size. Values are then assigned to these outcomes dicating their desirability. These values (C + NVC) e measured as changes in management costs and source values from conditions without fire. Costs include all expenditures associated with fire suppression tivities. Resource value changes may be either ositive or negative and may include effects—both of e fire and of suppression activities—on fisheries, ildlife, recreation, forage, timber, water (yield, orage, and quality), soils, air quality, visual quality, ilderness amenities, fuel hazards, improvements/ ructures, and public/social conditions (public con-rn, firefighter and public safety, cultural resources, ivate property, and employment).

In a highly explicit model, means for specifying and edicting fire effects and their associated values ould likely involve consideration of several additional ctors besides fire size, possibly including the nature d distribution of local vegetation, soil type, stage of enological development, fuel and soil moisture condi-ns, behavior of the fire, mesoscale atmospheric con-tions that affect smoke dispersal, and the prevailing cial and political climate. A great wealth of litera-re deals with the physical and biological effects of es vis-a-vis the production of various resource bene-s, and much of it has been summarized and synthe-zed in a number of state-of-knowledge reviews (Lotan al. 1981, Lyon et al. 1978, Martin et al. 1979, Sand-rg et al. 1979, Tiedemann et al. 1979, Wells et al. 79, Wright 1978). Despite the scientific interest in s topic, however, many important questions remain answered, and conflicts in existing evidence suggest at the needed answers will not be easily obtained. any EFSA decisions, therefore, would likely require plicit consideration of most of these factors, incor-rating judgmental assessments of physical, biolog-l, social, and political effects where sound scientific a are unavailable.

Means for valuating the predicted effects of wild-s and associated suppression activities are, in neral, not well developed either. Expected suppres-n costs for any chosen alternative can be estab-ed with a relatively high degree of reliability, but ource value change estimates are not as easily de-d. Resource components that characteristically e no established market (e.g., wildlife habitat, vis-amenities, and recreation opportunities) pose a sig-icant source of uncertainty for fire valuation efforts.

Although a large share of the published fire valua-n work has dealt strictly with marketable resources Gorte and Gorte 1979), several comprehensive proced-rs have been proposed for valuating all wildland fire fects (Bakker 1975; Crosby 1977; Marty and Barney 91; U.S. Department of Agriculture, Forest Service 9a, 1980b). The fact that these procedures involve o siderable detail and numerous manual tabulations ugests that some modifications would be necessary e re they could be useful for EFSA decisions.

Perhaps the most promising of the above approaches s the Forest Service Fire Management Analysis and Planning procedure for fire valuation (U.S. Department of Agriculture, Forest Service 1980b). It is not less complex than the others, but presumably, for Forest Service units, it will have been completed in the development of the forest plan. Thus, fire damage and benefit estimates, on a per-burned-acre basis, will be available for each resource category by locally recognized fire size and behavior classes.

Alternatively, all effects and values could be assessed directly by judgmental means. Even if nonjudgmental methods are used where possible, some effects and values will necessarily remain judgmental (e.g., safety and visual quality). This topic is developed more fully in the Discussion section.

Analysis

Once the possible outcomes have been evaluated and specified in terms of effects and values, they are aggregated into a single index, C + NVC. Assuming C + NVC has been expressed on a per-acre basis, these index values are multiplied by the number of acres burned to produce a total C + NVC estimate for each possible outcome. Finally, the *expected* value of each alternative is calculated by multiplying the total C + NVC for each outcome by the occurrence probability of the outcome and summing these products over all outcomes. Using the example in figure 1 to illustrate this computation, the expected C + NVC for alternative A ($E_A\{C + NVC\}$) is:

$$E_A\{C + NVC\} = wp(C + NVC)_w + x(1 - p)(C + NVC)_x \quad [1]$$

where p is the probability of success for alternative A, w is the area burned if A is successful, x is the area burned if A fails, and $(C + NVC)_w$ and $(C + NVC)_x$ are the net value changes (per unit area) for success and failure, respectively. Alternatives may then be compared directly on the basis of expected C + NVC.

Although the example offered in figure 1 is oversimplified, it serves to illustrate the general approach used to model the EFSA decision in this case study. Once represented by a decision analytic model, a specific EFSA decision can be analyzed in several ways. In addition to identifying the preferred suppression strategy given current information, value of information analyses (Howard 1966) can be conducted to guide information gathering or research activities to support the EFSA, and sensitivity analyses can be performed to determine the effects of model parameter variation. For example, varying weather conditions to see when a different strategy becomes preferred can provide guidance as to what weather changes may require a new EFSA. Some examples are described more completely for the case study application discussed below.

An Application

As an initial test of the use of decision analysis in the EFSA, a case-specific decision analytic model was tailored for a particular EFSA. The Wallowa-Whitman (W-W) National Forest in northeastern Oregon was

selected for the test application; the forest staff aided in the selection of an escaped fire situation that had been worked out previously as part of a training exercise—the Beaver Creek Fire. The salient conditions of the situation are as follows:

Location: The fire started at 2000 hr on August 11, 1980, at an elevation of 5780 feet within the La Grande City watershed (45°11′ N, 118°14′ W) (fig. 2). It was detected by aerial observer roughly 14 hours later— at 0955 hr on August 12.

Fire Behavior: At 1030 hr, when the EFSA is initiated, the fire is 2 acres in size, and is spreading to the northeast at 4-5 chains per hour. Flame lengths are estimated at 4-6 feet, corresponding to a fireline intensity of 100-300 Btu·foot^{-1}·second^{-1}. This intensity range is generally regarded as marginal for effective direct attack on the fire.

Weather: The wind is out of the southwest at 10-12 miles per hour. The temperature is 78° F, relative humidity is 34% and 10-hr timelag fuel moisture (Deeming et al. 1977) is 7%. The forest has been at the top of the "High" (3H) manning class for 14 days, and no change is forecast.

Fuels: The fire is burning in a large, continuous stand of lodgepole pine (*Pinus contorta* Dougl.), with moderate to heavy mortality and downfall due to a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) infestation. Fuel models used for fire danger rating in the fire vicinity include: dense conifer with heavy detritus (G), short-needle conifer (H), and medium logging slash (J) (Deeming et al. 1977).

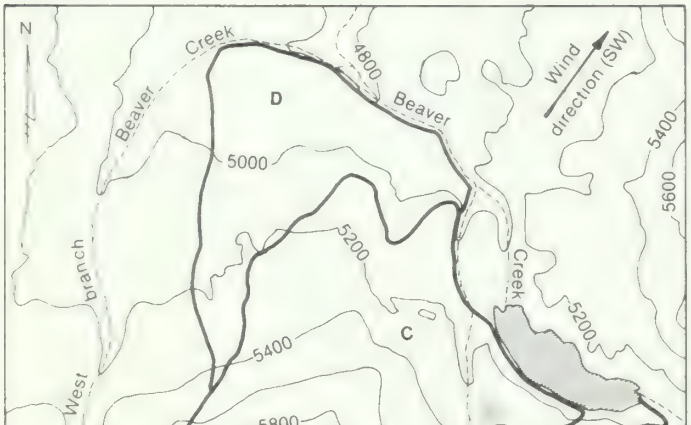

Figure 2.—Map of fire vicinity showing proposed fireline locations.

Alternative designation	Description	Estimated control time: Date	Estimated control time: Hour	Size if successfu (acres)
A	—Stop fire at top of first ridge —Parallel attack —Use retardant and jumpers —Build hand line and burn out	8/12	2400	15
B	—Stop fire midslope before it drops into Cove Creek —Same tactics as A	8/12	2400	80
C	—Stop fire at Cove Creek —Indirect attack with hand tools —Use Cove Creek and road as line for backfiring	8/13	1000	600
D	—Stop at reservoir intake road —Anchor and backfire from road —Begin parallel line with tractor and pinch off	8/14	1000	1000

Figure 3.—Description of alternative suppression strategies.

Resources: Because of relatively small stem size, a depressed wood market, and heavy bark beetle mortality, the immediate fire area is characterized as low investment timber. Sustained spread to the northeast, however, will involve old-growth allocations of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). The fire is entirely within the La Grande City watershed, which produces some special concerns about siltation or other damage to the water system, and public interest is expected to be high.

Forest Service personnel identified four possible alternative strategies (fig. 3). Proposed fireline locations for the four strategies are shown in figure 2 above.

These alternatives were not necessarily mutually exclusive. In fact, they could be implemented sequentially, i.e., if A fails, try B, etc. In some such cases, however, the sequential strategy would produce higher costs and lower probability of success for the subsequent strategy.

An additional alternative (not shown in figures 2 and 3) was proposed to serve as an indication of the worst that could happen if no other strategies were successful. This alternative, E, called for stopping the fire at a distant, relatively bare ridge after the fire consumed about 10,000 acres. Throughout this analysis, it was assumed that the fire could be stopped there with probability one.

Figure 4 shows the basic decision tree for this problem. Initially, the choice (square node) is among the five alternatives. Then, whichever is chosen may succeed or fail with some probability (circular node). If it fails, any subsequent strategy can be selected; again, it may succeed or fail. This figure shows the expected C+NVC associated with each of the five alternatives. Alternative B is the preferred initial alternative identified by this decision analysis, primarily because of the relatively low probability of success for alternative A. These expectations were calculated using the probabilities of success shown at the chance (circular) nodes and the C+NVC values associated with each tip of the tree, which are also shown. The derivation of these quantities is discussed in the following sections. Uncertainties

garding wind, fuel moisture, slope, fuel type, fireline tensity, spotting/crowning, and rate of spread have en incorporated either directly or indirectly (e.g., rough use of manning classes to represent weather d fuel moisture) in the calculation of the probabilities success nodes.

The analysis suggestion that B might be preferred to (although they are relatively close in value) was con- ary to the intuitive judgment of W-W staff. Several potheses regarding this difference are discussed llowing the description of the analysis, as are other sults.

obability of Success

Fuels were modeled by developing alternative sce- rios composed of mixes of fuel types. The fuel types ed were represented by National Fire Danger Rating stem fuel models G, H, and J (Deeming et al. 1977). ese scenarios, developed by W-W staff, are meant to representative of possible fuel situations existing in e vicinity of the fire. Probabilities for the various enarios were assessed by W-W staff. The scenarios d their assessed probabilities are shown in table 1. cause different alternatives include different areas, e fuel scenarios vary from alternative to alternative.

Rather than explicitly considering separate weather rameters in modeling the influence of possible

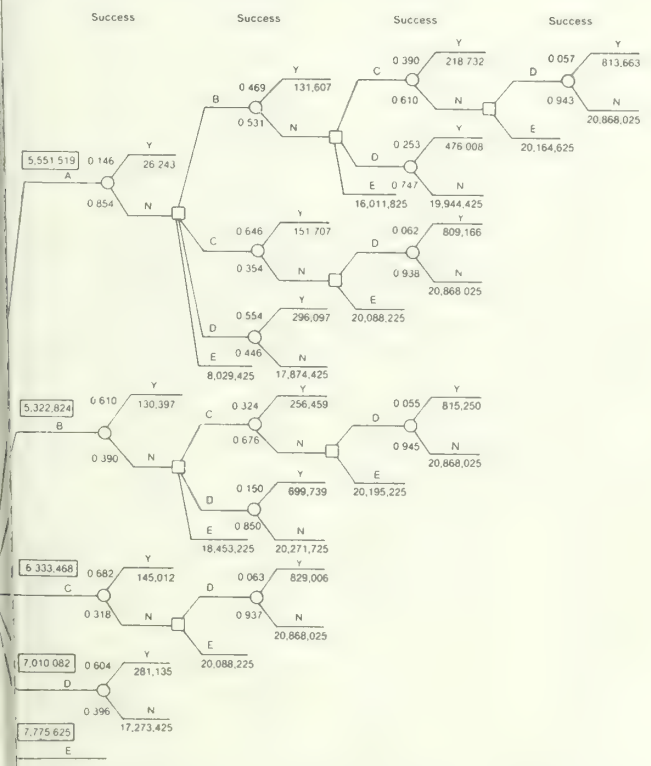

Figure 4.—Decision tree for Wallowa-Whitman National Forest Escaped Fire Situation Analysis. Enclosed numbers are the expected values (losses) of the five suppression alternatives, represented by A, B, C, D, and E. Success of the preceding strategy is represented by Y, and failure by N.

Table 1.—Fuel scenario definitions and probabilities

Alternative	Scenario	Probability	Fuel type percentage G	H	J
A	1	0.10	50	50	0
	2	.20	50	0	50
	3	.50	33	33	33
	4	.20	0	0	100
B	1	.40	0	80	20
	2	.60	10	70	20
C	1	.50	20	60	20
	2	.50	15	75	10
D	1	.40	20	50	30
	2	.60	10	65	25

weather scenarios on strategy success probabilities, fire weather conditions were represented by National Fire Danger Rating System manning classes, which integrate the various influential weather variables. The W-W National Forest uses six manning classes:

1 = Low
2 = Moderate
3L = Bottom of High
3H = Top of High
4 = Very High
5 = Extreme

They represent in ascending order more severe fire weather conditions. The manning class at the time of the fire was 3H and the fire danger forecast indicated it would remain 3H. Thus, uncertainty regarding weather was modeled by estimating a probability distribution over actual manning classes given the 3H forecast issued by the National Weather Service. That is, manning class probability estimates were made conditional on the National Weather Service fire danger forecast. This was accomplished by jointly examining the historical weather observation and forecast records of the nearest weather station (Furman and Brink 1975) with an adequate length of record (from the Johnson Rock Weather Station), for the period from July 15 to August 15, which was determined to be the most representative period. Separate estimates were required for the various fuel types because, for this study, manning classes were defined separately for the different fuel models. These conditional probability estimates are given in table 2.

Table 2.—Probabilities of manning classes, given the National Weather Service forecast

Actual manning class	Fuel type G	H	J
1	0.05	0.04	0.00
2	.07	.02	.08
3L	.29	.35	.32
3H	.50	.51	.43
4	.05	.04	.13
5	.04	.04	.04

Fire behavior was defined by three intensity (I) classes and three rate-of-spread (ROS) classes. Forest Service staff indicated that appropriate intensity classes would be

Class	Btu·foot^{-1}·second^{-1}
I_1 (low)	0-100
I_2 (medium)	100-700
I_3 (high)	>700

Rate-of-spread classes were

Class	Feet·minute^{-1}
ROS_1 (low)	0-10
ROS_2 (medium)	10-25
ROS_3 (high)	>25

Probabilities for these classes were also estimated using historical weather data for July 15 to August 15 from Johnson Rock Station. Data were processed for each of the fuel models, using the National Fire Danger Rating System (Deeming et al. 1977) fire behavior processor, which is built upon the Rothermel (1972) fire spread model. Intensity probabilities, shown in table 3, were conditional on manning class and fuel type, and ROS probabilities, table 4, were estimated conditional on fire intensity class and fuel type. Conditions required for spotting and/or crowning did not occur during the period of record examined, and W-W staff concurred that these severe fire behavior phenomona are rarely observed in areas similar to that being modeled.

Wallowa-Whitman National Forest fire management personnel provided assessments of the probability of success for each of the alternative strategies, given the various fire behavior characteristics. Only four behavior classes needed to be considered. The local experts indicated that if either ROS or intensity were in the high class, any alternative other than E would not be successful. In addition, several other combinations of intensity and ROS were not possible, given the probabilities in tables 3 and 4. Thus, the four types of fire behavior considered were

FB_1 ..... Low intensity and low ROS
FB_2 ..... Medium intensity and low ROS
FB_3 ..... Medium intensity and medium ROS
FB_4 ..... High intensity or high ROS

The assessed probabilities of success for possible strategy sequences, given the fire behavior class, are shown in table 5. Note that alternative E is always successful regardless of fire behavior and whether or not any other strategies have been attempted previously.

This information provides the basis for calculating the overall probability of success at any node in the decision tree (fig. 4). The derivation of these success probabilities is discussed in the appendix.

Costs and Value Changes

Suppression costs were estimated by W-W fire suppression specialists using standard Forest Service worksheets. These cost estimates are shown in table 6.

Table 3.—Fire intensity class probabilities, conditional on manning class and fuel type

Manning class	Fuel type	Fire intensity class		
		I_1	I_2	I_3
1	G	1.00	0.00	0.00
	H	1.00	.00	.00
	J	0.61	.39	.00
2	G	.50	.50	.00
	H	1.00	.00	.00
	J	.00	.53	.47
3L	G	.00	1.00	.00
	H	1.00	.00	.00
	J	.00	.00	1.00
3H	G	.00	1.00	.00
	H	1.00	.00	.00
	J	.00	.00	1.00
4	G	.00	1.00	.00
	H	1.00	.00	.00
	J	.00	.00	1.00
5	G	.00	.83	.17
	H	1.00	.00	.00
	J	.00	.00	1.00

Table 4.—Rate-of-spread probabilities, conditional on fire intensity class and fuel type

Fire intensity class	Fuel type	Rate-of-spread class		
		ROS_1	ROS_2	ROS_3
I_1	G	1.00	0.00	0.00
	H	1.00	.00	.00
	J	0.90	1.00	.00
I_2	G	.43	.57	.00
	H	1.00	.00	.00
	J	.39	.61	.00
I_3	G	.00	.00	1.00
	H	.50	.40	.10
	J	.01	.71	.28

Table 5.—Probabilities of success given fire behavior class and the sequence of strategies attempted

Alternative[1]	Fire behavior class			
	FB_1	FB_2	FB_3	FB_4
A	0.60	0.00	0.00	0.00
AB	.65	.40	.00	.00
ABC	.80	.60	.18	.00
ABCD	.70	.55	.20	.00
ABD	.90	.65	.30	.00
AC	.90	.60	.20	.00
ACD	.70	.55	.20	.00
AD	.90	.65	.30	.00
B	.80	.50	.00	.00
BC	.80	.60	.18	.00
BCD	.70	.55	.20	.00
BD	.90	.65	.30	.00
C	.90	.60	.20	.00
CD	.70	.55	.20	.00
D	.90	.65	.30	.00

[1] *Probabilities are for the last alternative listed in the row. Other alternatives indicate those attempted previously. For example, ABC indicates that alternative A and B were attempted before attempting C, and the success probabilitities are for C, taking into account these previous attempts.*

The values, both resource and social, that W-W staff ıdicated could be changed as a result of the fire in- ıude the following:

- visual quality
- wildlife
- fish
- wood production
- recreation
- forage
- water quality
- water storage
- fuels
- public concern
- employment
- public safety
- firefighter safety

The amount of change depends on the size and inten- ty of the fire. W-W staff estimated the relative agnitude of the changes for each of the three fire in- nsity classes and each of the five possible fire sizes etermined by the five alternatives) on a per acre basis. These assessed changes are shown in table 7. Changes in all areas except public concern and firefighter safety were assessed as percentages of the status quo (no fire). (W-W staff felt most comfortable with the judgments when they were structured this way.) Public concern and firefighter safety were rated directly.

In order to calculate a single measure of NVC, relative values of changes in each category were needed. Thus, in addition to the estimates of the possible resource production changes, W-W staff provided assessments of the tradeoffs among various resource changes. This was accomplished by using a procedure advocated by Edwards (1977) based on an approximation of additive multiattribute utility measurement (Keeney and Raiffa 1976). In this procedure, the worst possible and the best possible changes in each resource category were first identified. These ranges are shown in table 8. Then W-W staff were asked to consider these ranges and rank the resource categories according to the relative worth of moving from the worst end to the best end of the range shown in table 8. Ratio judgments were then made of the relative values for categories having adjacent rank scores. For example, the relative value of the difference between a 10% (worst possible) and a 20% (best possible) improvement in forage production, the category ranked next-to-last, was judged to be 1.5 times as valuable as the difference between a 10% (worst possible) and a 20% (best possible) reduction in fuel hazard, the category ranked last (table 8). The next judgment was then that the possible range of changes in public concern was 1.1 times as valuable as that for forage production. After all such judgments were made, relative weights were derived for each category (e.g., the weight for public concern was $1.1 \times 1.5 = 1.65$) and normalized to sum to 1.0.

Firefighter safety was assigned the highest weight of all considerations (table 8), while, as might be expected for a municipal watershed, potential damage to the

Table 6.—Fire suppression costs (dollars) given fire behavior class and the sequence of strategies attempted

ternative	Fire behavior class FB1	FB2	FB3
A	27,923	(1)	(1)
AB	140,192	358,324	(1)
ABC	294,275	294,275	606,247
ABCD	534,036	603,743	669,876
ABD	489,941	553,893	614,565
AC	291,361	291,361	600,245
ACD	534,036	603,743	669,876
AD	489,941	553,893	614,565
B	140,192	358,324	(1)
BC	294,275	294,275	606,247
BCD	534,036	603,743	669,876
BD	489,941	553,893	614,565
C	291,361	291,361	600,245
CD	534,036	603,743	669,876
D	489,941	553,893	614,565
E	2,430,225	2,430,225	2,430,225

[1] *Alternative would not be successful for this fire behavior.*

Table 7.—Fire effects on a per acre basis by fire intensity class and fire size[1]

esource/ ılue	Fire intensity class: I1 with Fire size (acres) of: 15	80	600	1,000	10,000	I2 with Fire size (acres) of: 80	600	1,000	10,000	I3 with Fire size (acres) of: 10,000
irefighter safety	1	2	3	3	5	10	20	25	30	100
/ater storage	−3	−3	−3	−3	−3	−10	−10	−10	−10	−25
/ood production	−5	−5	−5	−5	−5	+5	+5	−15	−15	−50
ecreation	0	0	+30	+30	+30	0	+30	+30	−10	−20
isual quality	0	+10	+10	+10	+10	+10	+10	+10	+10	−15
/ildlife	+5	+5	+3	+3	0	+10	+5	+5	−5	−30
isheries	0	0	−10	−15	−25	0	−15	−20	−30	−35
mployment	0	0	0	0	0	0	0	0	0	+10
ublic safety	0	0	0	0	0	0	0	0	0	−5
/ater quantity	+5	+5	+5	+5	+5	+10	+10	+10	+10	+15
ublic concern	0	15	60	65	100	15	60	65	100	500
orage production	+20	+20	+20	+20	+20	+10	+10	+10	+10	+10
uels/hazard reduction	+30	+30	+20	+15	+10	+30	+10	+10	+10	+50

[1] *All effects are percentage changes from the status quo, except public concern and refighter safety which are direct ratings. Note that a 15-acre fire would not occur with the iddle fire intensity, and only a 10,000-acre fire would occur with the high intensity.*

Table 8.—Ranges and weights for value changes

Resource/value	Range		Rank	Normalized weight
	Worst	Best		
Firefighter safety	100	1	1	0.186
Water storage	−25%	−3%	2	.168
Wood production	−50%	−5%	3	.142
Recreation	−20%	+30%	4	.103
Visual quality	−15%	+10%	5	.077
Wildlife	−30%	+10%	6	.071
Fisheries	−35%	0%	7	.065
Employment	0%	+10%	8	.062
Public safety	−5%	0%	9	.041
Water quantity	+5%	+15%	10	.032
Public concern	500	0	11	.021
Forage production	+10%	+20%	12	.019
Fuels/hazard reduction	+10%	+50%	13	.013
Sum				1.000

water storage system was considered the most important resource concern.

These weights were used to trade off all changes into a single measure of total change in utility. From an operational standpoint, it may not be desirable to aggregate all effects into a single measure of utility. Rather, it may be more appropriate to track various categories of effects as separate indexes, allowing the line officer the freedom to trade off these separate estimates in a nonexplicit fashion. In this analysis, however, we chose to represent the entire decision process as explicitly as possible; all effects were expressed in terms of a single utility index, C + NVC.

In this case, wood production was the common measure because a dollar value could be assigned; this then allowed the analysts to combine NVC with costs. The W-W staff estimated that the value of timber lost if all timber value were destroyed would be approximately $1,000/acre. By using this information and the ranges and weights in table 8, value changes in other resources can be traded off into dollars. For example, in considering effects on wildlife, from table 8

$$\frac{{}^{w}WL}{{}^{w}WP} = \frac{0.071}{0.142} = \frac{1}{2} \qquad [2]$$

where w is the weight assigned to the particular resource, and WL and WP are subscripts for wildlife and wood production, respectively. Since the value of a 100% loss of wood production is $1,000/acre, the value of the 45% difference between best and worst is $450/acre. (All values are assumed to be linear ove the range in consideration.) The difference betwee worst and best for wildlife (a range of 40%) is then ha this value or $225/acre, and the value of each percer change in wildlife is $225/acre ÷ 40% = $5.625/acr The resulting overall NVC's per acre for the variou alternatives and fire intensities are shown in table The effect of varying the value of wood production i discussed in the following section.

Table 9.—Net value changes per acre (dollars) given final strategy and intensity class

Alternative	Intensity class		
	I_1	I_2	I_3
A (15 acres)	+112	(1)	(1)
B (80 acres)	+192	−106	(1)
C (600 acres)	+295	−108	(1)
D (1,000 acres)	+262	−167	(1)
E (10,000 acres)	+165	−590	−2119

[1] *If attempted, this alternative would not be successful given the indicated fire behavior (see table 5).*

The expected total C + NVC for any fire shown i figure 4 was computed as

$$C + NVC = \sum_i P(FB_i)\, C_i + A\left(\sum_j P(I_j) NVC_j^A/ac\right) \qquad [3$$

where $P(FB_i)$ = the probability of fire behavior class i ($i = 1, \ldots, 4$),
C_i = the cost of suppressing a fire of type i,
$P(I_j)$ = the probability of a fire with intensity j ($j = 1, 2, 3$),
NVC_j^A/ac = the net value change per acre produced by a fire of size A with intensity j, and
A = the number of acres burned.

Supplemental Analyses

Two types of analyses can provide relevant informa tion in addition to that produced by the basic decisio analysis. Sensitivity analyses can indicate the robust ness of the results and which inputs produce any lacl of robustness. Value of information analyses (Howar 1966) can guide the collection of additional informatio to reduce uncertainty in the decision situation.

In this analysis, it is quite apparent from the mode (fig. 4) that varying cost and value parameters will no produce a significant change in the results (i.e., in th sense that a different alternative would be preferred) This can be seen by comparing alternatives A and B i the model. If alternative A fails, the subsequent struc ture of the problem is the same as if B had been th first strategy attempted, since if A fails, B has a lowe expected C + NVC than C, D, or E. The C + NVCs i these two parts of the tree are quite similar, and an changes in cost and value parameters would have rela tively little *differential* effect on expected C + NVC.

Nonetheless, the sensitivity of results to the dolla value of an acre of timber was examined explicitly. Th results presented above used a nominal value o $1,000/acre. Also considered were values of $500/acr and $2,000/acre, which is equivalent to halving an doubling *all* resource values, and the basic result were found to be unchanged. At $500/acre, alternativ A had an expected C + NVC of $3,157,801; B was stil preferred with an expected C + NVC of $3,034,348; and C, D, and E were correspondingly higher. Similarly with a value of $2,000/acre, the expected C + NVC o alternative A was $10,338,951 and of B, $9,899,778, while the others were again higher.

The best possible information, and therefore the in formation with maximum value, would be to know

which strategies would succeed and which would not. That is, the information would indicate one of five situations: (1) that A would succeed; (2) that A would not succeed and B would; (3) that A and B would not succeed and C would; (4) that A, B, and C would not succeed and D would; or (5) that no strategy except E would succeed. Contributing to the overall uncertainty in likelihood of success for each alternative, of course, are the individual uncertainties of weather, fuels, topography, fire behavior, and control effectiveness. The value of perfect information on which strategies would succeed and which would not provides an indication of the expected value of removing all uncertainty in these information components through research or additional information gathering.

In order to calculate the expected value of this information, we first must know the probability that each of the five possible situations will occur: $P(A)$, $P(\bar{A}B)$, $P(\bar{A}\bar{B}C)$, $P(\bar{A}\bar{B}\bar{C}D)$, and $P(\bar{A}\bar{B}\bar{C}\bar{D}E)$, where $P(\bar{A}B)$ denotes the probability that A fails and B succeeds. Each of these joint probabilities can be decomposed into conditional probabilities and $P(\bar{A}) = 1 - P(A)$, e.g.,

$$P(\bar{A}\bar{B}\bar{C}\bar{D}E) = P(E|\bar{D})P(\bar{D}|\bar{C})P(\bar{C}|\bar{B})P(\bar{B}|\bar{A})P(\bar{A}). \quad [4]$$

The conditional probabilites were calculated in a manner similar to those at the nodes in figure 4, except in each case the probabilities of success given the fire behavior were those for the specified strategy when it was not preceded by any other strategy (i.e., table 5 line entries A, B, C, and D). These probabilitites were used because, of course, if the information indicates exactly which strategies succeed and which do not, none of the ones that do not would be attempted. For example, if the information were that A and B would not succeed but C would, then obviously A or B would not be attempted before C. Thus, since $P(\bar{A}\bar{B}C) = P(C|\bar{B})P(\bar{B}|\bar{A})P(\bar{A})$, it is calculated as follows from the information in tables 5 and A-1. $P(\bar{A}) = 1 - P(A)$, which is found by multiplying the entries for alternative A in table 5 by the corresponding entries for alternative A in appendix table A-1 and summing over the four fire behavior classes. Similarly, $P(\bar{B}|\bar{A}) = 1 - P(B|\bar{A})$, which is found using alternative B in table 5 and alternative AB in table A-1. $P(C|\bar{B})$ is calculated using alternative C in table 5 and alternative $\bar{B}C$ (fire behavior at C given B has failed) in table A-1.

The probabilities of these five situations are as follows:

$$\begin{aligned} P(A) &= 0.146, \\ P(\bar{A}B) &= 0.493, \\ P(\bar{A}\bar{B}C) &= 0.128, \\ P(\bar{A}\bar{B}\bar{C}D) &= 0.020, \text{ and} \\ P(\bar{A}\bar{B}\bar{C}\bar{D}E) &= 0.213. \end{aligned}$$

Given this information, the expected C + NVC is then calculated as before, using equation [3]. The probabilities of fire behavior and intensity classes are calculated as described in the appendix, and costs and NVC estimates come from tables 6 and 9, respectively. Note that costs are those for alternatives not preceded by attempting other alternatives, e.g., the costs for situation $(\bar{A}\bar{B}C)$ are those from the "C" row in table 6. Thus, costs (and C + NVC) are always less than or equal to those on the top branches of figure 4 where some costs are increased by previous attempts at other strategies.

For each of the five possible situations, the expected C + NVC's are \$26,243, \$131,607, \$215,519, \$760,269, and \$20,868,025, respectively, producing an overall expected C + NVC of \$4,556,395. The difference between this figure and the expected C + NVC of the optimal strategy (B) in figure 4, \$5,322,824, yields the expected value of this information, \$766,429. This value reduces to \$432,773 if timber has a value of \$500/acre, and increases to \$1,433,744 with timber valued at \$2,000/acre.

Discussion of Application

When W-W staff had previously evaluated this EFSA as a training exercise, they had determined that alternative A was the preferred strategy. Although the present analysis suggested that A was only slightly less attractive than B, it may be useful to consider why this result differed from the previous result. Three hypotheses are apparent. One results from a possible inadequacy in this analysis; another results from a possible bias in the current EFSA decisionmaking process; and a third could be produced by either an inadequate analysis or biased judgment.

This analysis did not take into account attitude toward risk. The implications of the values in figure 4 suggest that A might become preferred to B if risk attitude were considered. Intuition regarding this can be guided by considering the outcomes of selecting A or B. The choice is between the two gambles shown in figure 5, with outcomes being the expected C + NVC resulting from the values in figure 4. Although B has the better expected value, as risk aversion increases, preference will shift more toward A. Intuitively, this means the desire to avoid a loss increases more rapidly than the amount of the loss does. The choice of strategy A by the W-W staff may be a manifestation of risk aversion.

Alternatively, the model may adequately capture the relevant features of the decision problem. The W-W staff choice may result from an institutionalized bias toward keeping the burned area as small as possible,

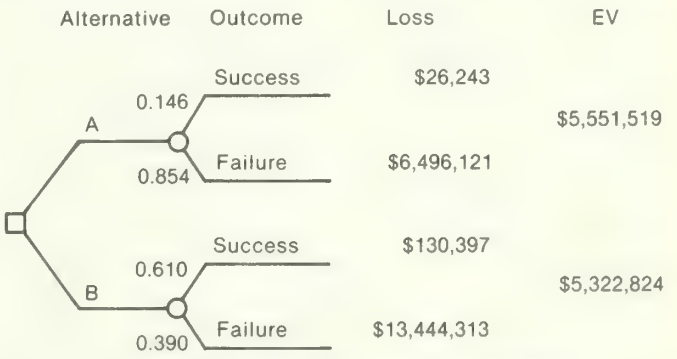

Figure 5.—Alternatives A and B as gambles.

i.e., toward stopping the fire at 15 acres (alternative A), if at all possible. Historically, this has been the Forest Service approach to fire suppression, and as such it may be ingrained in the thinking of fire management staff.

The third hypothesis is that the decision analysis generally gives a higher probability to fire behavior becoming more extreme than does the intuition of the forest staff members. The fire scenario as described included a statement that the manning class had been 3H for 14 days and no change was in sight. The decision analysis model, by incorporating historical probability distributions conditional on forecast weather, assigned probabilities of 0.08 to 0.17, depending on the fuel type, to higher manning classes actually occurring (table 3), while the forest staff may simply have assumed that the manning class forecast would be accurate. More severe conditions, of course, tend to support alternative B over alternative A.

Another point to be made regarding this application concerns the value of the best possible information. Such information would improve the expected value of the strategy decision by only about 14%. The reason for this is that the potential sequential nature of the strategies conforms rather closely to the optimal decision process given the perfect information. The reductions in the probabilities of success for a particular strategy caused by having taken some other strategy previously are rather small (nowhere more than 0.15), and the increase in costs is also small (always less than 10%). Perfect information would be of more value in a situation where alternatives could not be sequentially attempted, or where if they could be, it would be only with substantial changes in costs and/or probabilities of success. This does suggest, however, the value of identifying robust sequential strategies.

Discussion

Although the decision analytic model appears to have captured the basic features of the EFSA decision situation, a major problem that must be addressed before any implementation would occur is its size and complexity. No decisionmaker performing an EFSA would be interested in providing the assessments that were required for this model or in manipulating the model to ask "what if."

Two approaches to resolving this problem should be considered. The model can be simplified, for example, by using only the tree as shown in figure 4 without complex side models for determining the probabilities of success. These probabilities could be assessed directly at the time of use. A problem with this approach, however, would be the difficulty of Forest Service personnel accurately assessing these probabilities. These assessments would require consideration of complex factors, such as the relative likelihood of various fire behavior characteristics (and the variables that affect fire behavior) and how these likelihoods change as a result of attempting strategies. Comparison of probabilities assessed directly with those arrived at by modeling such as described here may provide useful insights on this question.

A second approach to solving the size and complexity problem is to provide most of the inputs to the model prior to use. Such inputs would essentially be default values that could be modified on-line if needed or desired. Development of the inputs would be done as a combination of research, training, and linking the decision analysis to existing data bases such as AFFIRMS (Administrative and Forest Fire Information Retrieval and Management System) (Helfman et al. 1975).

The approach to be taken in simplifying the model will depend to some extent on the degree to which the application described here is representative of most EFSA's. Specifically, it will depend upon whether generally, strategies can be attempted sequentially, or whether, in many cases, alternatives are available that cannot be sequentially implemented. Much of the complexity of the model developed here is caused by the sequential nature of the strategies and the attendant effects on probability assessment. Additional EFSA decision situations must be examined to guide the design and development of a decision analytic approach to real strategy decisions on escaped wildfires.

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Appendix A

Derivation of Success Probabilities

At each node in figure 4, the probability of success, P(S), is

$$P(S) = \sum_{i=1}^{4} P(S|FB_i)\, P(FB_i) \qquad [A1]$$

where FB_i ($i = 1,...,4$) is the fire behavior class. $FB_1 = I_1 \cap ROS_1$, $FB_2 = I_2 \cap ROS_1$, $FB_3 = I_2 \cap ROS_2$, and $FB_4 = I_3 \cup ROS_3$, where I_1, I_2, and I_3 are low, medium, and high intensities, and ROS_1, ROS_2, and ROS_3 are low, medium, and high rates of spread. For an alternative where no other strategy has been attempted previously,

$$P(I_i \cap ROS_j) = \sum_k P(F_k) \sum_m \left\{ w_m^{F_k} P(ROS_j|MOD_m, I_i) \times \sum_l [P(I_i|MC_l, MOD_m) \times P(MC_l|MOD_m)] \right\} \qquad [A2]$$

where F_k = fuel scenario k,

$w_m^{F_k}$ = the proportion of fuel model m in scenario F_k,

MC_l = manning class l, and

MOD_m = fuel model m.

Also,

$$P(FB_4) = P(I_3 \cup ROS_3) = 1.0 - \sum_{n=1}^{3} P(FB_n).$$

Thus, the fire behavior probabilities vary across alternative strategies because the fuels differ among the strategies.

For alternatives where another strategy has been previously attempted, these probabilities are modified to reflect information gained as a result of knowing that a previously attempted strategy failed. For example, alternative A can succeed only if the fire has low intensity and low ROS. If we know A has failed, this suggests that the probability of a low intensity-low ROS fire is reduced. A heuristic model was developed to reflect this information:

$$P(FB_i|st_j) = \alpha_{i,j} \div \sum_{i=1}^{4} \alpha_{i,j} \qquad [A3]$$

where $\alpha_{i,j}$ is defined by the following recursive equation:

$$\alpha_{i,j} = P(FB_i|st_j^1) - [P(S_{st_{j-1}}|FB_i)\alpha_{i,(j-1)} + P(FB_i|st_{j-1}^1) - \alpha_{i,(j-1)}] \qquad [A4]$$

and

$$\alpha_{i,1} = P(FB_i|st_1^1)$$

and where st_j = the secondary strategy being considered,

st_j^1 = that strategy with no previous strategy attempted,

$P(S_{st_{j-1}})$ = the success probability of the previously attempted, unsuccessful strategy.

Any $\alpha_{i,j}$ with a computed value less than zero is set equal to zero.

Intuitively it is known that a certain proportion of the fires that fall into a particular fire behavior class could be successfully stopped by the previously attempted strategy. When the first strategy fails, the percentage of fires expected in this fire behavior class must be reduced by this proportion in considering the success probability for the next strategy. In effect, this is a filtering process, whereby fires with a given class of behavior are sequentially filtered out by potential successes with previous strategies.

The resulting probabilities for fire behavior classes with the various sequences of suppression strategies are given in table A-1. These probabilities and those shown in table 5 are combined using equation [A1] to produce the probabilities of success at the chance nodes in figure 4.

Table A-1.—Occurrence probabilities for the various fire behavior classes given the sequence of strategies attempted

Alternative	Fire behavior class			
	FB_1	FB_2	FB_3	FB_4
A	0.243	0.131	0.176	0.450
AB	.701	.032	.042	.225
ABC	.342	.132	.207	.319
ABCD	.000	.036	.186	.778
ABD	.147	.106	.174	.573
AC	.638	.083	.110	.169
ACD	.000	.048	.178	.774
AD	.534	.069	.093	.304
B	.745	.027	.036	.192
BC	.241	.146	.241	.372
BCD	.000	.033	.186	.781
BD	.016	.116	.202	.666
C	.690	.071	.094	.145
CD	.000	.049	.179	.772
D	.602	.059	.079	.260

[1] *Probabilities are for the last alternative listed in the row. Other alternatives indicate those attempted previously. For example, ABC indicates that alternative A and B were attempted before attempting C, and the fire behavior probabilities are for C, taking into account these previous attempts.*

Seaver, David A., Peter J. Roussopoulos, and Anthony N. S. Freeling. 1983. The Escaped Fire Situation: A decision analysis approach. USDA Forest Service Research Paper RM-244, 12 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

A preliminary, decision analysis model addressing the choice among alternative suppression strategies on escaped wildfires is presented. A case study application of the model, in the context of an Escaped Fire Situation Analysis on the Wallowa-Whitman National Forest, is described and discussed.

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Research Paper RM-245
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

USDA Forest Service
Research Paper RM-245

June 198

Bird Response to Timber Harvest in a Mixed Conifer Forest in Arizona

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Abstract

A mixed conifer forest in eastern Arizona was harvested by a combination of group and individual tree selection. Some small patches ranging in size from 1/2 to 3 acres were clearcut. Total bird numbers were slightly lower after timber cutting, but the number of species observed increased from 28 to 35. Analysis of bird species by nesting and feeding guilds showed no significant differences in numbers before and after cutting for any of the guilds.

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Virgil E. Scott and Gerald J. Gottfried

Management Implications

Timber harvesting in southwestern mixed conifer orests should not adversely affect bird density or pecies diversity, provided removals are less than 30% o 40% of the stand basal area. This study, at Thomas reek in eastern Arizona, evaluated changes in a bird opulation before and after an operational timber arvest designed to benefit several resources. Bird opulation changes were also compared with an uncut tand. The silvicultural prescription for the virgin, neven-aged forest called for group selection on south-acing slopes and for individual tree selection with atch clearcutting on the north-facing slopes. Patches ere from 0.5 to 3.0 acres. The harvest removed from 4% to 34% of the total stand basal area, and from 28% o 37% of the overstory basal area. Sixty-eight acres ere in patchcuts and in openings created by the group election. A net volume of 3.4 million board feet was arvested.

The harvest resulted in only minor changes in bird opulations. Bird numbers decreased slightly (12%) but the number of species increased from 28 to 35. House wrens,[3] American robins, and pine siskins were new additions to the area's bird population. There were no significant differences in bird numbers when analyzed by nesting and feeding guilds. The ruby-crowned kinglet was the only major species to show a significant decrease.

A previous study by Szaro and Balda (1979) in a ponderosa pine forest showed that moderate harvesting by either strip shelterwood or by a silvicultural improvement cut did not adversely affect the bird population. In contrast, heavy overstory reductions by clearcutting or heavy thinning (82% reduction in basal area) in ponderosa pine (Szaro and Balda 1979), or by diameter-limit cutting in mixed conifers (Franzreb 1977), did reduce bird densities and, often, species diversity.

There are still other harvesting prescriptions sufficiently different from the Thomas Creek cut or from those reported in the literature that should be studied before a predictive model for bird management in mixed conifer forests can be developed.

Introduction

Birds are an important forest resource because of eir ecological role and recreational value. Logging ractices alter habitat conditions and may affect spe-es composition and densities. Bird populations appear respond differently, depending on the amount and istribution of trees removed. Szaro and Balda (1979) ound species diversity and density decreased on a earcut plot of ponderosa pine and density decreased n a severely thinned plot, whereas bird numbers in-reased where timber reductions were less drastic. ranzreb (1977) found that bird density decreased when e basal area of a southwestern mixed conifer stand as reduced 84%, although number of species in-reased slightly.

Southwestern mixed conifer forests occupy about 1/2 million acres of high-elevation lands in Arizona nd New Mexico (Jones 1974). The forests usually grow bove 8,000 feet, except on protected north slopes and nyon bottoms, where they occur down to 6,000 feet. he mixed conifer forest is a highly diversified type, ith a wide mixture of stand structures and with up to ght tree species. The type is an important avian abitat with as many as 53 species of birds (Franzreb 77).

Timber harvesting practices in the Southwest are designed primarily for timber production; however, water yield improvement is possible. Rich and Thompson (1974) indicated that increases in water yield are positively related to the percentage of the watershed that is cleared. Periodic harvests of trees in small groups and clearcuts are compatible with recommended silvicultural methods for mixed conifers (Alexander 1974) and provide successional stages of regeneration for use by a variety of wildlife. The timber harvest on the Thomas Creek watershed was an attempt to develop a silvicultural prescription that would benefit timber management, wildlife, water yield, and aesthetics. This report summarizes the response of nongame birds to the timber harvest.

Study Area

The Thomas Creek watersheds are located in eastern Arizona on the Apache-Sitgreaves National Forests, about 15 miles south of Alpine. Objectives of the Thomas Creek investigation were to design and evaluate a multi-resource management program for the southwestern

[3]*Scientific names of trees and birds are listed in Appendix I.*

mixed conifer forest type (Brown 1976). Two watersheds (South Fork and North Fork) were instrumented with weirs to measure water yields and sediment. Timber was harvested from the South Fork watershed, whereas the North Fork watershed was uncut and maintained as a control (fig. 1).

Some important watershed characteristics are:

Characteristic	South Fork	North Fork
Size (acres)		
South-facing slope	311	327
North-facing slope	251	140
Elevation (ft)	8,350-9,150	8,350-9,250
Slope, average (%)	22	27

Soils on both watersheds are generally sandy loams derived from basalt parent material.

Annual precipitation, measured near the South Fork weir, averaged 29.2 inches from 1964 through 1980. About 55% fell from October through May mainly as snow. During the summer (May to August), the mean daily maximum temperature was 72° F; the mean daily minimum was 42° F, and the daily mean temperature was 57° F.

Both watersheds originally supported a virgin, uneven-aged mixed conifer forest (fig. 2) consisting primarily of eight tree species: Engelmann spruce, blue spruce, Douglas-fir, white fir, corkbark fir, ponderosa pine, southwestern white pine, and quaking aspen. Gambel oak is an important minor species. The usual stand consists of a mosaic of groups and patches of varying sizes and species composition. Thomas Creek has not had a major fire in over 90 years. Douglas-fir is the most common species on the watersheds, whereas ponderosa pine is the most commercially valuable (tables 1 and 2). North Fork has numerous young ponderosa pine thickets, which accounts for the relatively high density of trees (table 2). The open, mature ponderosa pine overstory on the south-facing slopes above the North Fork weir contributes to the lower average basal area for that unit.

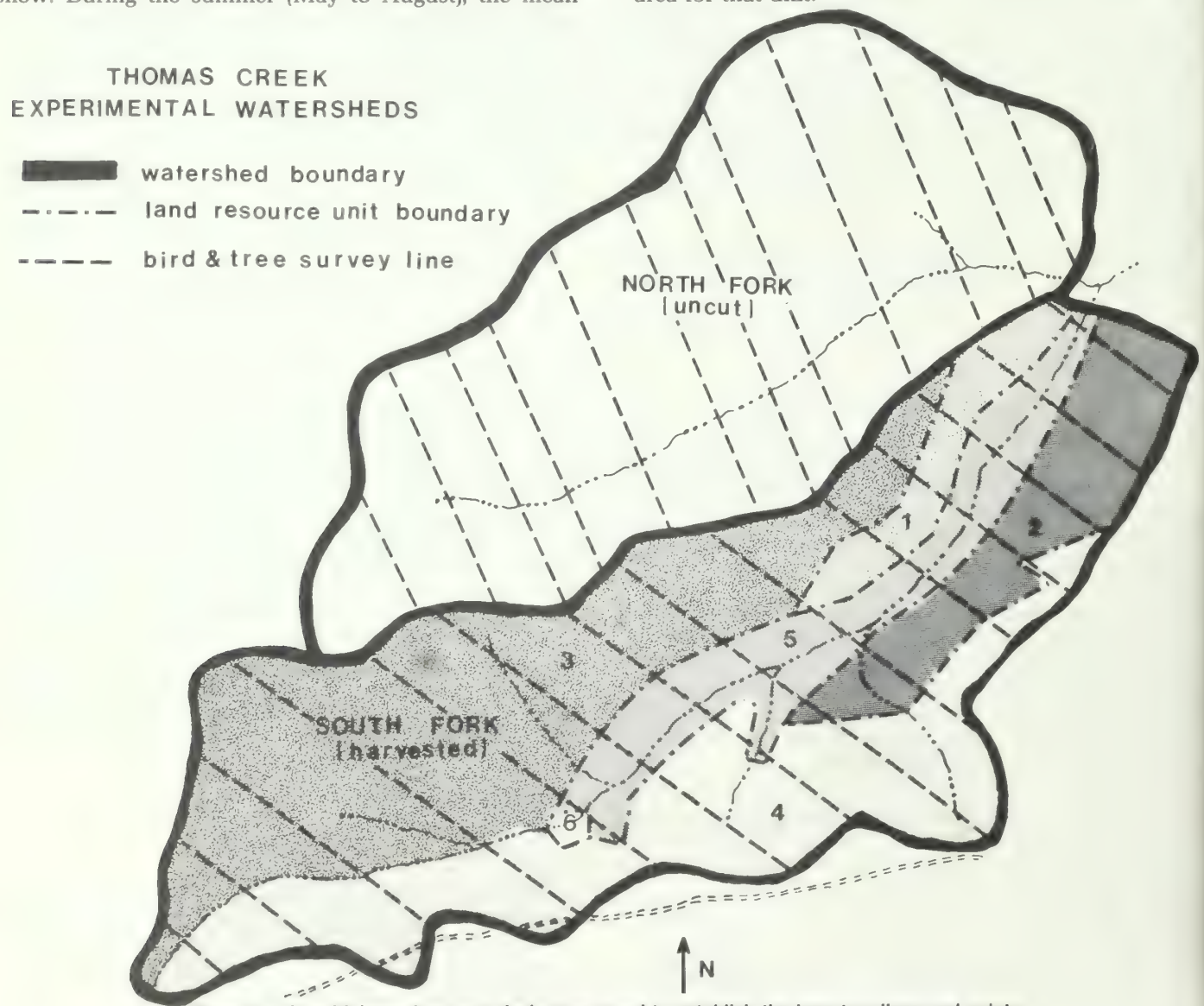

Figure 1.—A multiple-random start design was used to establish the inventory lines and points on North and South Fork of Thomas Creek. South Fork was divided into 6 land response units for evaluating treatment alternatives.

ıe Prescription

Management activities to be evaluated on South Fork ere a combination of silvicultural practices designed consider wildlife, water, and timber resources. South ork watershed was divided into six land response units RU). The silvicultural prescription for LRU 5 was in-vidual tree selection; for units 1 and 3, group selection signed to reduce the basal area by 30%; and for units and 4, clearcut patches with individual tree selection vay from the clearcuts (fig. 1). However, units 1, 2 and e downstream half of unit 5 were not harvested be-use of the locally steep slopes.

ıe Harvest

Timber harvesting began in May 1978 and continued termittently through January 1979. A net volume of 3.4 illion board feet was harvested. This included some lume that was salvaged from trees which blew down fall 1978.

In group selection unit 3, the cutting operation eated 41 small openings about 0.5 acre or larger. tal area opened was about 35 acres. Thirty-three res were patchcut in unit 4, creating 25 openings (fig. The average patch clearcut was about 1.3 acres hough they varied from 0.5 acre to about 3.2 acres.

Slash was lopped in all areas except fuelbreaks and ng watercourses. Larger material (greater than 8 hes diameter inside bark) was skidded to designated dings. Slash was machine piled with a 330-foot wide lbreak which ran along the perimeter of the harvest a and in a 200-foot fuelbreak along the logging roads. was hand piled along the channel. Slash was piled in cleared patches that were within fuelbreak zones. es were constructed in July 1979 and burned in Oc-er 1980.

ire 2.—Both watersheds supported a dense, multi-storied mixed conifer forest before harvest.

Figure 3.—Looking into a small patch-cut from the single-tree selection area on a north-facing slope.

Methods

Vegetation Measurements

Forest vegetation was measured in 1974, before treatment, and in 1979 after harvesting was completed. All forest stand data were collected at permanent timber inventory points using standard point sampling techniques based on a 25 basal area factor (BAF) angle gage. Points were established according to a multiple-random start design. A total of 128 points, located at 264-foot intervals, were established on the 14 South Fork lines. However, because the steep areas were not harvested, measurements were concentrated on 59 points on the south-facing slope and 35 points on the north-facing slope. Samples were collected at 119 points on the 12 North Fork lines (fig. 1).

Stand values, in terms of average number of trees per acre and average basal area (square feet) per acre, were calculated using standard point sampling procedures (Husch et al. 1972). To show the vegetation available to birds, the 1979 data reflects changes caused by growth of trees measured in 1974 and surviving to 1979, natural mortality and harvesting, and new trees which were initially measured during the 1979 survey.

Changes in stand composition were analyzed by chi-square tests for significance ($\alpha = 0.05$). Diameter distributions were analyzed by transformed linear regressions (Husch et al. 1972) and covariance analyses.

Bird Densities

Birds were censused on the watersheds in spring and early summer 1974 and 1975 before any timber was cut. Posttreatment surveys were conducted in 1979-1980. Censuses were conducted along established timber in-

Table 1.—Pre- and posttreatment stand characteristics for the treated portion of South Fork of Thomas Creek Watershed

	Trees (No./acre)[a]				Basal area (ft²/acre)[b]			
	North exposure		South exposure		North exposure		South exposure	
	Before harvest	After harvest	Before harvest	After harvest	Before harvest	After harvest	Before harvest	After harvest
Aspen	45	38	49	44	21	18	19	17
Ponderosa pine	79	75	18	11	24	16	34	18
White fir	76	36	37	86	46	25	37	29
Corkbark fir	17	18	2	5	7	7	2	2
S.W. white pine	110	46	38	44	15	8	23	20
Douglas-fir	105	84	134	168	65	39	67	51
Blue spruce	13	10	5	7	13	9	3	3
Engelmann spruce	32	67	11	10	19	17	9	8
Total	477	374	294	375	210	139	194	148

[a]*One acre = 0.4047 hectare.*
[b]*One square foot per acre = 0.2296 square meters per hectare.*

Table 2.—Stand characteristics for (untreated) North Fork of Thomas Creek Watershed by exposure in 1974 before treatment on South Fork

	Trees (No./acre)[a]		Basal area (ft²/acre)[b]	
	North exposure	South exposure	North exposure	South exposure
Aspen	71	16	28	4
Ponderosa pine	1	166	3	65
White fir	233	86	63	22
Corkbark fir	68	2	18	1
S.W. white pine	7	71	6	19
Douglas-fir	79	277	52	50
Blue spruce	4	0	2	2
Engelmann spruce	172	2	36	2
Other	0	84	0	4
Total	635	704	209	166

[a]*One acre = 0.4047 hectare.*
[b]*One square foot per acre = 0.2296 square meters per hectare.*

ventory transect lines, which ran perpendicular to the drainage in each watershed. The South Fork transect lines totaled 4.6 miles and the North Fork lines were 4.2 miles. Censuses began at sunrise and continued for 3.5 hours. Three days were required to census all transect lines on each watershed. Two censuses were made on each watershed each year. For each bird observed we recorded bird species, location, sex (if possible), activity, distance from survey line, and the tree species being used by the bird. We estimated bird numbers by first calculating the mean observation distance from the transect for each species. This was assumed to be one-half of the effective distance censused (Amman and Baldwin 1960). Bird numbers were then determined by using two times the mean observation distance times transect length to determine the area censused. Differences in numbers of birds between drainages before and after timber harvest were tested for significance ($\alpha = 0.05$) by a two-factor repeated measures analysis of variance by species and by feeding and nesting guilds. A diversity profile for birds was prepared following Patil and Taillie (1979). Differences in numbers of birds by exposure were tested by a "t" test ($\alpha = 0.05$).

Results

Vegetation

Before harvest, basal area differences between the two slopes of South Fork were minor (table 1), but there were differences in the species distribution of trees. On North Fork (table 2), the proportion of trees and basal area per acre were different between the two slopes for most species.

Diameter distributions for the total stand were different between the north- and south-facing slopes of South Fork because of the proportionately larger number of overstory trees (d.b.h. < 7.0 inches) on the south-facing slopes (39%). A comparison of south-facing

opes between watersheds also showed differences ecause of the proportions of overstory trees. Only 14% f the trees on the south-facing unit of North Fork were 7.0 inches d.b.h. Comparisons of the two slopes on orth Fork, and between the north-facing slopes of the vo watersheds, showed no differences in d.b.h. of ees.

Timber harvest on South Fork resulted in a 22% eduction in the total number of trees per acre on the orth-facing slope (table 1) and a 34% reduction in asal area per acre. The south-facing slope showed a 3% increase in number of trees, reflecting increased rowth of smaller trees, particularly white fir. Basal rea on this slope decreased by about 24%. The harvest ad a greater effect on the overstory component of the and. The total reductions in number of overstory trees er acre were 12% for the south-facing slope and 30% r the north-facing slope. Basal area reductions were 3% and 37%, respectively. Most of the changes were e result of timber harvest, although some trees died ter of natural causes and were left in the woods.

Harvesting did not affect relative basal area composi- on within either area. Relative overstory composition ithin units did not change because of treatment. Com- arisons between slopes showed relatively more ouglas-fir and white fir on the south slope and more ngelmann spruce, corkbark fir, and ponderosa pine on e north slope. Diameter distributions for both areas of outh Fork changed significantly after harvest, as ex- ected (fig 4).

Stand changes on North Fork during the study period ere minor, reflecting growth and natural mortality, hich mainly occurred in overmature ponderosa pine nd aspen.

ure 4.—Large, overmature trees have been harvested from this ection of the south-facing slope on the group selection method rea.

Bird Densities

Bird numbers varied considerably between years in the untreated area as well as the treated area (table 3). Bird estimates were lower by 12% on South Fork after treatment compared to a 3% reduction on North Fork, but the number of species increased from 28 to 35. Bird species observed on the uncut North Fork dropped from 29 to 27. Species found on South Fork after harvest, but not present before, included the house wren, (which made use of the slash piles left after harvest), American robin, and pine siskin. The bird diversity profile indicated that the uncut North Fork had a higher bird diversity than South Fork before timber harvest, but that diversity on South Fork was greater after timber harvest.

Twenty-two species were tested individually for significant changes in density levels before and after timber harvesting. Only densities of ruby-crowned kinglets were found to have changed significantly ($P = 0.05$). The difference was significant because of a large increase in kinglets on the uncut North Fork and a slight decrease on the harvested drainage.

Birds also were separated into foraging and nesting guilds (table 4) and tested for changes in numbers after treatment. No significant change was found for any of the guilds.

Total bird populations were not different by slope, but several birds favored either north or south exposures (table 3). Northern flickers, white-breasted nuthatches, red-faced warblers, and western tanagers were significantly more numerous on south-facing slopes, whereas ruby-crowned kinglets were more numerous on north-facing slopes.

Frequency of tree use by birds was compared with tree species composition. Birds were observed in aspen and Douglas-fir trees significantly more than if use were random. True firs (white and corkbark) were used less than would be expected.

Tree use by those birds with significantly higher densities on north and south exposures was compared in an effort to determine if tree species availability could explain preferences for exposure. Ruby-crowned kinglets, the only species with significantly higher density on north-facing slopes, used spruce, Douglas-fir, and white pine more than if use were random; ponderosa pine and the true firs were used less. Those birds more abundant on south slopes also utilized the true firs less than would be expected, but the use of Douglas-fir and ponderosa pine was greater. The difference in bird density by exposure probably cannot be explained by tree species composition.

Probably the only truly tree-specific bird was the warbling vireo. Aspen was used significantly more than would be expected by warbling vireos, whereas all other tree species except white pine were used significantly less.

Discussion

The silvicultural prescription for the timber harvest on South Fork watershed of Thomas Creek was designed

Table 3.—Estimated number of birds/100 ac on Thomas Creek Watershed in Arizona

Species	Densities by watershed				Densities by exposure							
	South Fork		North Fork (uncut)		South Fork				North Fork			
	Before harvest 1974-75	After harvest 1979-80	1974-75	1979-80	Mean 1974-1975 N.	Mean 1974-1975 S.	Mean 1979-1980 N.	Mean 1979-1980 S.	Mean 1974-1975 N.	Mean 1974-1975 S.	Mean 1979-1980 N.	Mean 1979-1980 S.
Williamson's sapsucker	4	2	5	4	3	6	1	3	7	4	7	2
Hairy woodpecker	10	3	6	5	15	4	2	3	0	8	0	7
Northern flicker	6	6	8	10	6	6	3	9	5	8	6	12*
Western flycatcher	21	11	12	8	13	25	14	9	10	13	28	0
Violet green swallow	2	9	0	12	0	3	5	12	0	0	5	15
Steller's jay	13	8	9	9	23	4	6	9	4	11	15	7
Mountain chickadee	49	40	34	15	55	50	39	42	47	28	18	14
Red-breasted nuthatch	4	10	3	2	6	4	3	15	7	2	3	2
White-breasted nuthatch	2	2	1	4	0	4	1	2	0	2	0	5*
Pygmy nuthatch	1	<1	9	6	0	2	<1	0	0	13	0	8
Brown creeper	20	8	19	16	12	27	0	11	13	22	38	8
House wren	0	17	0	2	0	0	22	13	0	0	0	2
Golden-crowned kinglet	17	4	19	<1	28	8	4	3	30	3	0	<1
Ruby-crowned kinglet	47	41	39	73	36	54	48	36	84	11	146	42*
Hermit thrush	23	10	16	12	29	19	10	12	12	18	5	15
American robin	0	5	0	0	0	0	2	2	0	0	0	0
Warbling vireo	22	20	16	12	13	30	18	21	15	17	21	8
Orange-crowned warbler	1	0	5	0	2	0	0	0	18	0	0	0
Yellow rumped warbler	60	62	57	85	48	70	28	90	56	59	89	83
Red-faced warbler	14	17	26	33	18	11	9	28	17	29	0	46*
Western tanager	10	9	14	2	0	19	3	13	0	20	0	3*
Dark-eyed junco	17	8	23	12	15	18	6	10	25	23	2	16
Pine siskin	0	11	11	3	0	0	11	10	13	11	0	3
Other birds[1]	0	1	3	1	0	0	1	0	0	4	0	0
Total birds	343	304	335	326	322	364	236	353	363	306	383	298

[1] *A complete list of birds observed on the study area is in the Appendix.*
* *Indicates significant differences ($\alpha = 0.05$) between north and south exposures.*

Table 4.—Estimated number of birds/100 ac. by guild on Thomas Creek

Guilds	South Fork		North Fork (uncut)	
	Before harvest 1974-75	After harvest 1979-80	1974-75	1979-80
Foraging guilds				
Pickers & gleaners	260	249	263	263
Ground feeders	46	29	47	34
Hammerers & tearers	14	6	13	9
Aerial feeders	23	20	12	20
Nesting guilds				
Cavities & depressions	119	109	99	84
Foliage nesters	184	177	197	218
Ground nesters	40	18	39	24

to benefit a variety of resources—timber, wildlife, and water. Although more than 3.4 million board feet were harvested, overall stand changes were not drastic. Total basal area on the north-facing slopes was reduced 34% where timber was cut in patches and by individual tree selection, and 24% on the south-facing slopes where the cutting was done by group selection. Reductions in overstory basal area were slightly higher. Trees per acre decreased on the north-facing slope by 22% but increased on the south-facing slope as a large number of new trees grew into larger size classes. Relative species basal area composition did not change within units.

Logging resulted in minor short-term changes in bird populations. Total estimated numbers dropped by 12%, but the number of species increased from 28 to 35. House wrens, absent before logging, used the resulting slash piles after timber cutting. Only the ruby-crowned kinglet was significantly less abundant after timber harvest.

In an adjacent mixed conifer watershed on Willow Creek, Franzreb (1977) found a significantly higher density of birds in an unlogged area compared with an area that was logged according to a diameter-limit prescription, which removed about 84% of the original basal area. In the cut area, aspen made up over 54% of the residual basal area. Ten species of birds, including American kestrel, yellow-bellied sapsucker, olive-sided flycatcher, house wren, and American robin increased

nd 13 species, including western flycatcher, mountain hickadee, and ruby-crowned kinglet, decreased. The rends for house wren, American robin, and ruby-rowned kinglet are consistent with our findings on Thomas Creek.

We conclude that a moderate timber harvesting operation that removes about 30% of the basal area of a tand, whether designed for multi-resource benefits or rimarily for timber production, will not adversely affect bird populations. More severe reductions in basal rea, such as the overstory removal on Willow Creek, nay reduce the total number of birds (Franzreb 1977).

The relationship we found between bird populations nd the severity of timber cutting in a mixed conifer orest tends to be consistent with results in southwestrn ponderosa pine (Szaro and Balda 1979). Bird populaon densities decreased significantly when ponderosa ine was clearcut or heavily thinned (from 120 to 22 quare feet per acre). In comparison to an untreated ontrol, they found that bird populations increased, as id species diversity and richness, where less severe, iregular strip shelterwood or improvement cuttings were pplied. Diversity and richness did not decrease on their eavily thinned plot. Total ponderosa pine and Gambel ak basal area can be reduced by between 15% and 0% in strips or blocks or by 30% in uniform thinning, vithout adversely influencing bird populations (Szaro nd Balda 1979).

For the welfare of nongame birds, Szaro and Balda 979) recommend that no more than 45% of trees over 9 nches d.b.h. be removed, leaving a minimum of 32 trees er acre, and that certain densities of smaller trees also e maintained. Snags and overmature trees should be ft for cavity-nesting birds.

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Appendix I

Common and scientific names of birds and trees found on the study area

	Bird Species
Turkey vulture	*Cathartes aura*
Sharp-shinned hawk	*Accipiter striatus*
Cooper's hawk	*A. cooperii*
Northern goshawk	*A. gentilis*
Red-tailed hawk	*Buteo jamaicensis*
American kestrel	*Falco sparverius*
Blue grouse	*Dendragapus obscurus*
Wild turkey	*Meleagris gallopavo merriami*
Band-tailed pigeon	*Columba fasciata*
Mourning dove	*Zenaida macroura*
Broad-tailed hummingbird	*Selasphorus platycercus*
Yellow-bellied sapsucker	*Sphyrapicus varius*
Williamson's sapsucker	*S. thyroideus*
Downy woodpecker	*Picoides pubescens*
Hairy woodpecker	*P. villosus*
Three-toed woodpecker	*P. tridactylus*
Northern flicker	*Colaptes auratus*
Olive-sided flycatcher	*Contopus borealis*
Western wood peewee	*C. sordidulus*
Western flycatcher	*Empidonax difficilis*
Purple martin	*Progne subis*
Violet-green swallow	*Tachycineta thalassina*
Steller's jay	*Cyanocitta stelleri*
Clark's nutcracker	*Nucifraga columbiana*
American crow	*Corvus brachyrhynchos*
Common raven	*C. corax*
Black-capped chickadee	*Parus atricapillus*
Mountain chickadee	*P. gambeli*
Red-breasted nuthatch	*Sitta canadensis*
White-breasted nuthatch	*S. carolinensis*
Pygmy nuthatch	*S. pygmaea*
Brown creeper	*Certhia familiaris*
House wren	*Troglodytes aedon*
Golden-crowned kinglet	*Regulus satrapa*
Ruby-crowned kinglet	*R. calendula*
Townsend's solitaire	*Myadestes townsendi*
Swainson's thrush	*Catharus ustulatus*
Hermit thrush	*C. guttatus*
American robin	*Turdus migratorius*
Solitary vireo	*Vireo solitarius*
Warbling vireo	*V. gilvus*
Orange-crowned warbler	*Vermivora celata*
Yellow-rumped warbler	*Dendroica coronata*
Red-faced warbler	*Cardellina rubrifrons*
Olive warbler	*Peucedramus taeniatus*
Western tanager	*Piranga ludoviciana*
Black-headed grosbeak	*Pheucticus melanocephalus*
Dark-eyed junco	*Junco hyemalis*
Pine grosbeak	*Pinicola enucleator*
Red crossbill	*Loxia curvirostra*
Pine siskin	*Cardeulis pinus*

	Tree Species
Engelmann spruce	*Picea engelmannii* Parry ex Engelm.
Blue spruce	*P. pungens* Engelm.
Rocky Mountain Douglas-fir	*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco
Rocky Mountain white fir	*Abies concolor* (Gord. and Glend.) Lindl. ex Hildebr.
Corkbark fir	*A. lasiocarpa* var. *arizonica* (Merriam) Lemm.
Rocky Mountain ponderosa pine	*Pinus ponderosa* Dougl. ex Laws.
Southwestern white pine	*P. strobiformis* Engelm.
Quaking aspen	*Populus tremuloides* Michx.
Gambel oak	*Quercus gambelii* Nutt.

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Keywords: Wildlife habitat, timber harvesting, clearcutting, wildlife populations

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Rocky Mountains

Southwest

Great Plains

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Forest Service

Rocky Mountain Forest and Range Experiment Station

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Research Paper
RM-246

Effects of Commercial Clearcutting of Aspen on Understory Vegetation and Wildlife Habitat Values in Southwestern Colorado

Glenn L. Crouch

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USDA Forest Service
Research Paper RM-246

August 1983

Effects of Commercial Clearcutting of Aspen on Understory Vegetation and Wildlife Habitat Values in Southwestern Colorado

Glenn L. Crouch, Principal Research Wildlife Biologist
Rocky Mountain Forest and Range Experiment Station[1]

Abstract

Commercial clearcutting of aspen in southwestern Colorado produced aspen sprouts, but caused relatively few lasting changes in other understory plant characteristics 5 years after logging. The most negative impact of logging on wildlife habitat was removal of the overstory, which adversely affected cavity-nesters and other species requiring mature forest.

[1]*Headquarters is in Fort Collins, in cooperation with Colorado State University.*

Effects of Commercial Clearcutting of Aspen on Understory Vegetation and Wildlife Habitat Values in Southwestern Colorado

Glenn L. Crouch

Management Implications

Aspen (*Populus tremuloides*) is clearcut in the central ocky Mountains to obtain wood products, to enhance s value as wildlife habitat, and to ensure its perpetuaon for scenic beauty. Clearcutting is especially impornt since much of the aspen is mature, and fire, its atural regenerative force, has been successfully supressed in recent years. Commercial clearcutting is robably the most economical method to renew aspen, ut usually requires logging relatively large acreages to ecover operating costs.

Except for overstory loss, clearcutting and removal of gs in more than 60 nearby blocks of mature aspen ranging in size from 2 to 20 acres resulted in few lasting changes in understory plant characteristics during 5 years after logging. Overstory removal adversely affected cavity-nesters and other species requiring mature forest, but clearing for roads and harvesting should benefit species needing sparsely vegetated areas and forest edges, and those favoring tall, dense, shrub-like habitats provided by aspen sprouts in older clearcuts.

In future sales, wildlife benefits can be enhanced by extending timber sales in local areas over 10 years or more or by making several sales periodically. These options would reduce the acreage of overstory removed at one time and also prolong benefits to species favoring forest openings.

Introduction

Aspen (*Populus tremuloides* Michx.) is the most abunant deciduous tree in the central Rocky Mountains. spen provides habitat for many wild birds and mamals, and may be essential for some species (Reynolds 969, Gruell and Loope 1974, Flack 1976, Armstrong 977, DeByle 1981). Aspen forests also produce large mounts of forage, offer shelter for livestock, and are ne of the outstanding scenic features of the Rocky Iountain states.

Aspen of sufficient size and soundness for wood prodcts grow throughout the central Rockies, but demand is rrently low in most areas. As economic values of spen timber increase, forest managers must learn how harvest aspen with maximum benefits to all reurces, including wildlife (Wengert 1976).

One of the few relatively stable markets for aspen gs is in southwestern Colorado, where the San Juan ational Forest has sold aspen stumpage regularly for ore than 30 years. A timber sale in the early 1970's oduced more than 60 clearcut blocks, ranging in size m 2 to 20 acres, that were logged between 1974 and 178. The sale area provided a unique opportunity to aluate major changes in wildlife habitat and use by lected herbivores that had occurred since cutting gan. The relative uniformity of the aspen stand, use of -to-date logging and slash disposal technology, and ailability of several clearcut blocks of various sizes in e different post-logging age classes, provided an unmmon chance to study plant succession and wildlife responses to commercial clearcutting in a short period of time.

This paper reports on logging-induced changes in understory vegetative characteristics that influence relative values of these aspen stands as wildlife habitat.

The Study Area

The study was conducted on west Stoner Mesa, about 25 miles northeast of Dolores, Colo. Elevations averaged about 9,200 feet in the gentle topography of that part of the sale area that was investigated. The site was occupied by a nearly pure stand of mature aspen averaging about 650 trees per acre, ranging from less than 1 to more than 20 inches d.b.h., and up to 90 feet in height (fig. 1). Basal area averaged 198 square feet per acre, and average site index was estimated at 60. Overstory cover averaged 85 percent (Crouch 1982). According to Dolores Ranger District records, about 600 acres, or 25 percent of the stand in addition to clearings for roads, was clearcut, mainly in the dormant season.

The overstory cover was dense and mostly resembled elements of the *Populus tremuloides/Symphoricarpos oreophilus* and *P. tremuloides/Thalictrum fendleri* habitat types described by Hoffman and Alexander (1980) on the Routt National Forest some 200 miles northeastward.

West Stoner Mesa provided spring, summer, and fall habitat for mule deer (*Odocoileus hemionus*), elk (*Cervus canadensis*), and seasonal habitat for other game and

nongame birds and mammals. Cattle also grazed there each summer.

Methods

Data on understory vegetation and herbivore use were collected from 18 different blocks. Fifteen were clearcut, with merchantable logs removed, and slash scattered. Among these, 3 blocks were selected from each year of logging and slash treatment, from winter 1974 through winter 1978. Within each year class, one block was selected from each of the following size classes: 2-7, 8-13, and 14-19 acres. All blocks were rectangular. In addition, one block corresponding to each size-class was established in uncut aspen as a control. These control blocks were isolated from clearcut blocks by at least 200 feet. The 15 clearcut blocks plus 3 controls made up the study sites.

Data were collected on two sampling lines established across the longer axis of each block. Lines were placed approximately equidistant from the block edges and from each other.

Plant Production and Ground Cover

Plant production was determined by clipping current growth of all understory vegetation within square, 1 square-foot plots located at 55-foot intervals along each sampling line. Aspen leaves, shrubs, grasses, and forbs were sacked separately, weighed green in the field, and later oven-dried at 55°C to determine moisture content.

Plant cover by species was measured in 1- by 2-inch rated microplots spaced 10 feet apart on each sampling line. Cover of all species within 5 feet of ground surface was estimated by 10-percent increments in microplots, as described by Morris (1973). Aspen sprouts were also inventoried in permanent plots at every fifth microplot location (Crouch 1982).

Figure 1.—Uncut aspen block on Stoner Mesa study area.

Production and cover were sampled near the peak of the growing season, in late July 1979.

Relative understory quality was evaluated by comparing crude protein content and dry matter digestibility derived according to procedures described by Regelin et al. (1974). Rumen inoculum from a domestic cow, fed grass hay, was used in digestibility determinations.

Herbage Utilization

Large herbivore use of grasses and forbs was estimated from differences in biomass of these plants inside and outside five, circular, 7.5 square foot wire cages erected 55 feet apart along one sampling line in each block. For these determinations, in late September grasses and forbs were clipped and sacked separately from one, square, 1 square-foot plot inside and outside each cage. Results are expressed in pounds per acre dry weight, determined by multiplying percent utilized by herbage available.

Large Herbivores

Big game and livestock activity was estimated in fall 1979, from fecal counts made on 8-foot wide transects extending along each sampling line in fall 1979.

Data Analysis

Analysis of variance ($P = 0.05$) was used to test for differences among year and size classes for all understory plant attributes and fecal counts on established transects. Tukey's test was used to separate means, where appropriate (Snedecor 1961). Orthogonal comparisons were used to test differences between uncut and the means of collective clearcut values within categories.

Results

Clearcutting completely removed the aspen overstory and replaced the 650 existing trees per acre with more than 30,000 sprouts per acre by the end of the first growing season after logging (Crouch 1982). Various amounts of slash also remained (fig. 2). By the second year after logging, aspen sprouts were the dominant visual growth form on clearcuts (fig. 3).

Plant Production

Except for the first year after logging, annual growth of woody plants was greater on clearcuts than on uncut blocks (Table 1).[2] The increase resulted mainly from a gain in aspen rather than from shrubs, which did not respond to logging.

[2]*Greater or lesser, increases or decreases, etc., indicate that values reported are significantly different at $P = 0.05$.*

Figure 2.—First-year clearcut on Stoner Mesa study area.

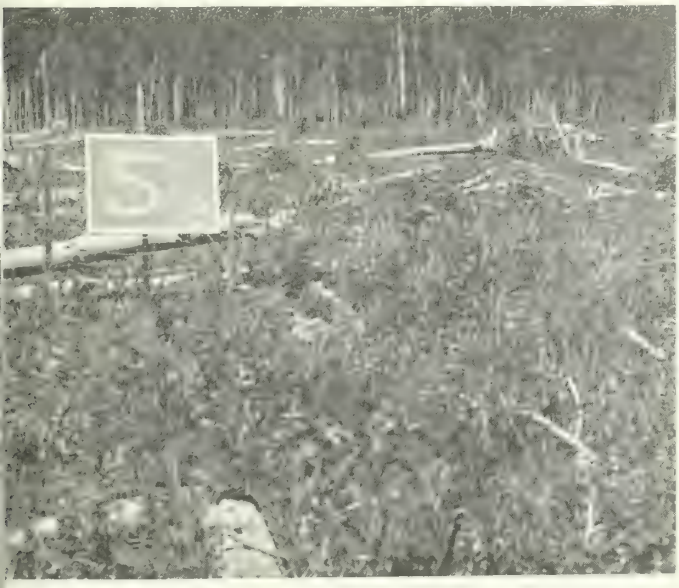

Figure 3.—Second-year clearcut on Stoner Mesa study area.

Graminoid (grass and sedge) production was lower on first-year clearcut blocks than on uncut or older clearcuts, but recovered quickly. The 5-year mean production on clearcuts was not different from that on uncut areas (Table 1). Quantities of forbs were depressed on first-year blocks, but not different from controls over the 5-year period, although production indicated a gaining trend on older blocks.

Total herbage production (graminoids and forbs) was not different on clearcuts compared to uncut blocks. Less herbage was present on first-year clearcuts, but quantities increased markedly thereafter.

Total amounts of understory vegetation were greater on clearcuts than on uncut blocks. Growth was suppressed on first-year clearcuts, but exceeded production on controls and in 2- to 5-year-old blocks. Block size had no effect on plant production.

Herbage Utilization

Herbivores, mainly cattle fed on vegetation on all blocks, and utilization was heavy on several of the clearcut areas (Table 1). Use of graminoids was greater on intermediate-aged clearcuts than on uncut or the newest and oldest logged blocks. Although use reached 80 percent of the available crop on two clearcut blocks, the overall averages were 21 and 43 percent of graminoids on the uncut and clearcut blocks, respectively. Quantities of forbs used were greater on older clearcuts than on uncut or newer blocks. Use rates reached 60 percent on two clearcuts near stock ponds, but averaged 24 and 33 percent on uncut blocks and among all clearcuts, respectively.

Ground Cover

Forbs were the dominant plant cover in the understory of uncut blocks (fig. 4, Table 2). Collectively, the 35 species of forbs recorded in microplots contributed 79 percent, graminoids 13 percent, and woody species 8 percent of the total cover.

Table 1.—Dry weight understory plant production (lb/acre) and herbage utilization (lb/acre) on uncut and clearcut aspen blocks on Stoner Mesa, San Juan National Forest, southwestern Colorado, 1979

Category	Uncut	Years since logging[1]					Uncut[2]	Clearcuts[2]
		1	2	3	4	5		
Aspen	20b	19b	382a	354a	477a	509a	20a	348b
Shrubs	136a	55a	158a	199a	204a	183a	136a	160a
All woody plants	156b	74b	541a	552a	681a	691a	156a	508b
Graminoids	392a	162b	378a	360a	372a	317a	392a	318a
Forbs	967b	566c	1,061b	1,164b	1,208b	1,574a	967a	1,115a
All herbage	1,359b	728c	1,439ab	1,524ab	1,581ab	1,892a	1,359a	1,433a
All plants	1,515b	802c	1,980a	2,076a	2,261a	2,583a	1,515a	1,940b
Herbage utilization								
Graminoids	81b	76b	160a	193a	163a	93b	81a	137b
Forbs	233b	199b	223b	477a	510a	459a	233a	374b

[1] *Within categories, values among years followed by the same letter are not significantly different (P = 0.05).*
[2] *Within categories, uncut and the mean value for clearcuts followed by the same letter are not significantly different (P = 0.05).*

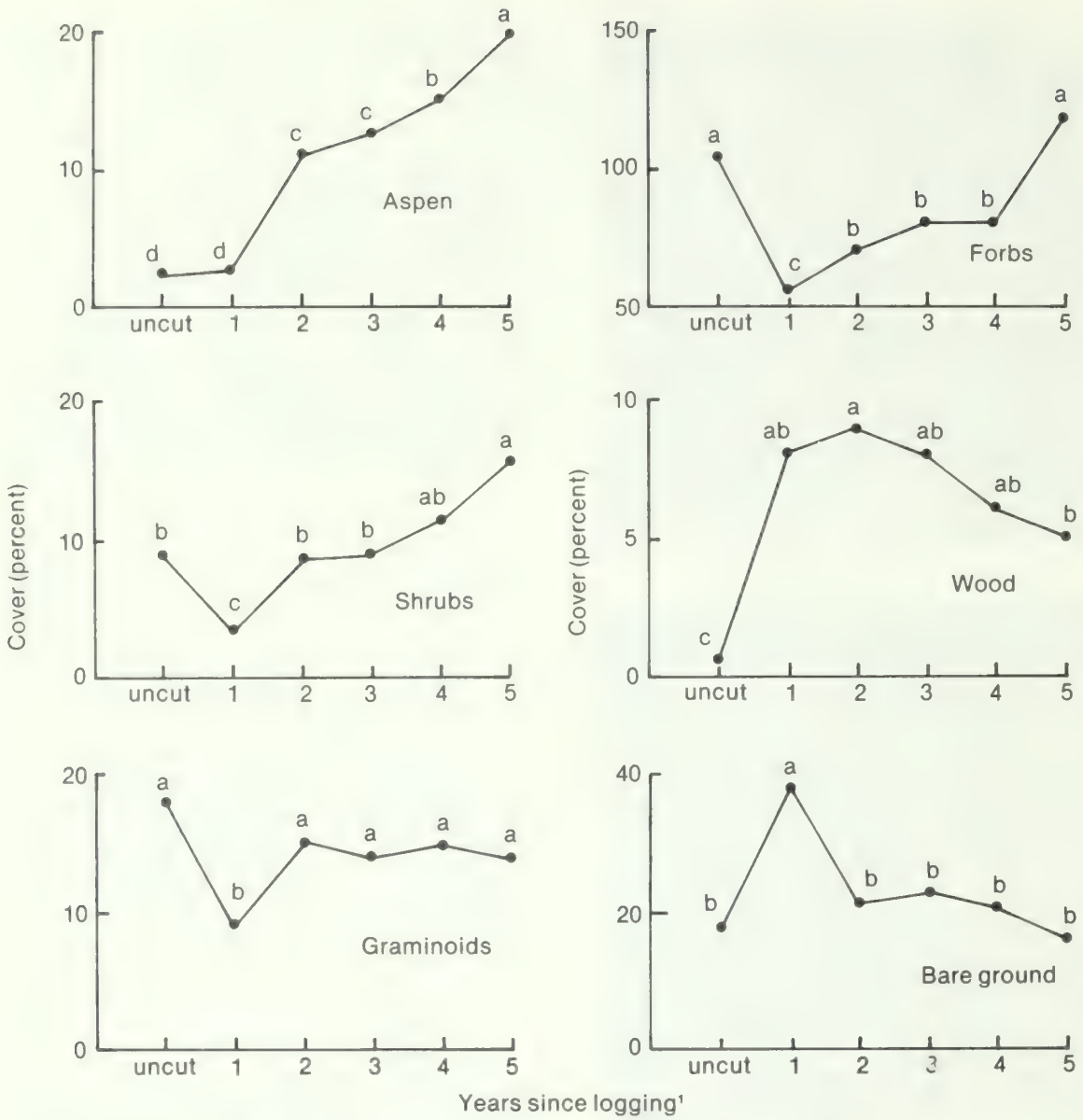

Figure 4.—Ground cover in clearcuts on Stoner Mesa study area. (Within categories, values among years followed by the same letter are not significantly different; P = 0.05.)

Individual species of understory plants were variously affected by clearcutting. Among woody plants, only aspen changed, increasing in cover over the 5 years after logging. Cover of the two most common grasses, *Poa pratensis* and *Elymus glaucus* was diminished by logging and had not recovered in fifth-year blocks. Cover of *Bromus ciliatus* was greater in older blocks than on the uncut or younger clearcuts.

Forbs showed the largest fluctuations among species. Cover of 7 of the 10 most abundant forbs was lower on first-year clearcuts than on uncut blocks (Table 2). On fifth-year sites, cover of six of these species was no longer different from controls, and cover of two species, *Ligusticum porteri* and *Achillea lanulosa*, exceeded that on uncut blocks. Among other forbs, only *Veratrum californicum* and *Smilacina stellata* were lower in cover on fifth-year blocks than on the controls, whereas *Osmorhiza obtusa* and *Mertensia franciscana* were more abundant 5 years after clearcutting.

Comparisons of cover of forb species on uncut blocks with that on clearcuts of all ages showed that annual means of 6 of the 10 leading species were lower on the clearcut areas during the 5 years after logging (Table 2).

Influence of block size on plant cover varied widely among species, and no consistent pattern of size effect was evident.

Cover of wood, including logging slash and natural mortality, which was negligible on uncut blocks, increased on clearcuts immediately after logging, and showed a declining trend thereafter (fig. 4). Compared with uncut blocks, amounts of bare ground doubled in first-year clearcuts, but had declined to levels found in the forest by the second, post-logging growing season.

Table 2.—Percent understory plant cover on uncut and clearcut aspen blocks on Stoner Mesa, San Juan National Forest, southwestern Colorado, 1979

Growth form and species[1]	Uncut	Years since logging[2]					Uncut[3]	Clearcuts[3]
		1	2	3	4	5		
Woody plants								
Symphoricarpos oreophilus	7.8abc	2.2c	4.9bc	8.1abc	9.7ab	11.8a	7.8a	7.3a
Populus tremuloides	2.2d	2.3d	10.8c	12.8bc	14.8b	18.9a	2.2a	11.9b
Rosa woodsii	0.9a	0.6a	1.6a	0.4a	0.6a	0.6a	0.9a	0.8a
Potentilla fruticosa	0.4a	0.6a	1.4a	0.2a	0.4a	1.4a	0.4a	0.8a
Graminoids								
Poa pratensis	6.4a	0.5c	2.7bc	2.6bc	2.1bc	3.3b	6.4a	2.2b
Carex festivella	5.4ab	4.2b	7.9a	6.9ab	7.8a	5.0b	5.4a	6.4a
Elymus glaucus	4.1a	2.6ab	3.9ab	3.1ab	0.9ab	0.3b	4.1a	2.2b
Bromus ciliatus	1.2b	1.0b	1.2b	1.4b	2.0ab	3.5a	1.2a	1.8a
Calamagrostis canadensis	0.8a	0.7a	0.7a	1.2a	1.1a	0.9a	0.8a	0.9a
Melica sp.	0.4a	0.1a	0.3a	0.1a	0.1a	0.2a	0.4a	0.2a
Forbs								
Erigeron speciosus	18.1a	5.8c	6.6bc	10.6bc	11.5b	20.0a	18.1a	10.9b
Thalictrum fendleri	18.0a	7.0c	8.5c	9.4c	11.3bc	16.3ab	18.0a	10.5b
Ligusticum porteri	12.1a	10.4a	8.5a	9.2a	11.7a	20.0b	12.1a	12.0a
Thermopsis montana	8.1a	2.7b	6.6ab	6.8ab	7.9a	7.2ab	8.1a	6.2b
Galium boreale	6.6a	4.1b	5.3b	7.0a	7.6a	6.0a	6.6a	6.0a
Fragaria ovalis	6.1a	2.7a	2.8a	2.7a	5.3a	5.0a	6.1a	3.7b
Lathyrus arizonicus	5.8a	2.2b	5.2ab	4.9ab	4.7ab	7.1a	5.8a	4.8a
Taraxacum officinale	4.7a	1.3b	4.7a	2.8ab	3.5ab	5.0a	4.7a	3.5a
Geranium richardsonii	3.5ab	0.9b	0.6b	1.5b	1.2b	4.2a	3.5a	1.7b
Achillea lanulosa	3.0c	0.7d	4.4bc	4.8abc	6.8a	5.9ab	3.0a	4.5b
Viola spp.	2.3a	0.6a	0.1a	0.9a	0.2a	1.4a	2.3a	0.6b
Osmorhiza obtusa	2.2b	0.4b	0.9b	0.9b	1.7b	4.9a	2.2a	1.8a
Veratrum californicum	2.2a	0.6b	0.2b	0.2b	0.9b	0.9b	2.2a	0.6b
Frasera speciosa	1.7a	0.3a	0.2a	0.3a	0.6a	0.7a	1.7a	0.4b
Cirsium spp.	1.2a	0.2a	6.0b	1.7a	2.8a	1.1a	1.2a	2.4a
Smilacena stellata	1.1a	0.1b	0.1b	0.1b	0.1b	1.1a	1.1a	0.3b
Allium textile	1.0a	0.5a	0.9a	0.1a	0.1a	0.1a	1.0a	0.3a
Helianthella quinquenervis	1.0a	0.0a	1.3a	0.0a	0.0a	0.4a	1.0a	0.3a
Pseudocymopterus montanus	0.9ab	0.3b	1.1ab	1.3ab	2.5a	0.4b	0.9a	1.1b
Vicia americana	0.9a	0.7a	1.2a	2.0a	1.0a	1.3a	0.9a	1.2a
Mertensia franciscana	0.8b	0.9b	0.1b	1.3b	1.4b	3.8a	0.8a	1.5a
Helenium hoopsesii	0.6a	0.1a	0.2a	0.1a	0.1a	0.1a	0.6a	0.1b
Potentilla gracilis	0.4a	0.2a	1.2a	0.2a	0.4a	1.5a	0.4a	0.7a
Solidago multiradiata	0.3a	0.7a	0.2a	1.8a	1.6a	0.9a	0.3a	1.0a
Chenopodium capitatum	0.3a	0.2a	0.1a	0.0a	0.1a	0.5a	0.3a	0.2a
Castilleja miniata	0.3a	1.0a	1.2a	0.8a	0.5a	0.1a	0.3a	0.7a
Pedicularis grayi	0.0a	2.1a	0.5a	0.9a	0.3a	1.0a	0.0a	1.0a

[1] *Two other shrub, four graminoid, and 8 forb species were also occasionally recorded in mircroplots.*
[2] *Within species, values among years followed by the same letter are not significantly different (P = 0.05).*
[3] *Within species, uncut and the mean value for clearcuts followed by the same letter are not significantly different (P = 0.05).*

Moisture Content

Moisture content of aspen leaves and shrubs from first-year clearcuts was higher than in those collected in uncut or older clearcuts (Table 3). Moisture in graminoids collected from first-year clearcuts was lower than in samples from uncut blocks and remained low on the older logged areas. Moisture in forbs from first- and second-year blocks was lower than in samples from uncut areas or older clearcuts. Comparisons of moisture amounts in plants from uncut areas with amounts in samples from all ages of clearcuts showed a significant difference only in graminoids (Table 3). Block size had no effect on moisture content.

Crude Protein

Aspen leaves and shrubs from newer clearcuts contained more crude protein than samples collected on uncut or older logged blocks (Table 4). The average content was higher in material from clearcuts collectively

Table 3.—Percent moisture content of understory vegetation on uncut and clearcut aspen blocks on Stoner Mesa, San Juan National Forest, southwestern Colorado, 1979

Category	Uncut	Years since logging[1]					Uncut[2]	Clearcuts[2]
		1	2	3	4	5		
Aspen leaves	65.8bc	71.1a	70.2ab	65.0c	63.4c	61.5c	65.8a	66.2a
Shrubs	63.8b	72.8a	60.1b	64.1b	60.6b	62.0b	63.8a	63.9a
Graminoids	71.5a	61.8b	59.9b	67.7ab	67.6ab	63.6b	71.5a	64.1b
Forbs	78.1ab	75.5c	74.3c	77.4ab	78.7a	79.0a	78.1a	77.0a

[1] *Within categories, values among years followed by the same letter are not significantly different (P = 0.05).*
[2] *Within categories, uncut and the mean value for clearcuts followed by the same letter are not significantly different (P = 0.05).*

Table 4.—Dry weight crude protein content (%) of understory vegetation on uncut and clearcut aspen blocks on Stoner Mesa, San Juan National Forest, southwestern Colorado, 1979

Category	Uncut	Years since logging[1]					Uncut[2]	Clearcuts[2]
		1	2	3	4	5		
Aspen leaves	16.7d	20.9b	22.1a	18.4c	18.7c	16.3d	16.7a	19.3b
Shrubs	13.9c	21.2a	16.1b	15.6b	15.6b	12.7c	13.9a	16.2b
Graminoids	11.7a	12.8a	11.9a	11.4a	12.7a	11.7a	11.7a	12.1a
Forbs	14.8a	14.3a	14.6a	14.4a	14.7a	14.6a	14.8a	14.5a

[1] *Within categories, values among years followed by the same letter are not significantly different (P = 0.05).*
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than in aspen and shrubs from uncut sites. Amounts of crude protein in graminoids and forbs were not different among year-classes of clearcuts or between samples from uncut and logged blocks.

Crude protein available in the standing crop of understory vegetation is shown in Table 5. Amounts were calculated by multiplying kg/ha of vegetation by percentage of crude protein content in the various growth form categories.

Aspen leaves and forbs contained the largest reservoir of crude protein. The amount contributed by aspen was low on first-year clearcut and uncut blocks because little aspen grew there. Amounts available in shrubs were unaffected by logging (Table 5).

Crude protein available in graminoids was lower on the newest clearcuts because quantities of these plants were lower there. The mean amount in graminoids among all clearcuts was not different from that on uncut blocks.

The quantity of crude protein in forbs was lower on first-year clearcuts and uncut blocks than in forbs on older clearcuts, but amounts in uncut blocks and mean quantities on clearcuts were not different.

Availability of crude protein in the total understory component was lowest in first-year clearcut and uncut blocks. Vegetation in clearcuts collectively, contained more crude protein per hectare than in uncut blocks.

Digestibility

In vitro digestibility of aspen leaves, shrubs, and graminoids in samples collected on first-year clearcuts was greater than in those obtained on older clearcuts or uncut blocks (Table 6). Digestibility of samples of these growth forms from the collective clearcuts was greater than samples from controls. Digestibility of forbs was unaffected by logging. Block size had no effect on digestibility.

Herbivore Activity

Numbers of cattle droppings were greater on older clearcuts than on uncut or recently logged blocks (Table 7). Cattle sign was also more prevalent on smaller than on larger blocks. Fewer deer pellet groups were observed on uncut and older clearcut blocks than on those more recently logged. Numbers of elk droppings were low and not different among clearcut and uncut blocks. Abundance of deer and elk sign was unaffected by block size.

The consumption of feces by unknown species of dung beetles on the Stoner Mesa area is assumed to have negligible effects on comparisons among the blocks studied, but may preclude comparisons of counts there with inventories elsewhere.

Discussion

After five years, commercial clearcut logging of aspen on Stoner Mesa had resulted in relatively few major changes in understory characteristics. Except for large increases in numbers of aspen sprouts, which were expected, other responses were minimal. Production of

shrubs, graminoids, and forbs was depressed on first-year clearcuts, but recovered to levels found in uncut blocks by the second year after logging. Among all plants, more vegetation was present on clearcuts collectively than on uncut blocks, but the difference was mainly attributed to more aspen on the logged blocks. Five years after logging, the cover of only one common grass, *Elymus glaucus*, and one uncommon forb, *Allium textile*, were declining compared with their presence on uncut or newer clearcut blocks.

Utilization of graminoids and forbs was greater in clearcuts and is attributed to the greater tendency of cattle to graze there than in the forest. Clearcutting on Stoner Mesa can probably be considered a range improvement practice for cattle.

The open character of the clearcuts immediately after logging was greatly diminished in older blocks, despite the presence of logging slash, roads, and bare ground resulting from yarding and log decks. Fifth-year clearcuts offered as much or more growing-season hiding cover to herbivores than the uncut forest (fig. 5). Observations made in 1981, on 7-year-old clearcuts, showed aspen sprouts exceeding 20 feet in height, with average canopy heights of about 8 feet. Although no measurements were taken at that time, it appeared that herbage production was declining as the sprout stands matured. The density of larger sprouts also appeared to impede the movement of large herbivores, whose activity seemed to be primarily on well-defined trails in the older blocks.

Although the timber sale was not specifically designed for wildlife benefits, the pattern of clearcutting and the logging practices employed appear to have had minimal adverse impacts and several favorable effects on the general suitability of the sale area as wildlife habitat.

Table 5.—Dry weight crude protein availability (lb/acre) from understory vegetation on uncut and clearcut aspen blocks on Stoner Mesa, San Juan National Forest, 1979

Category	Uncut	Years since logging[1]					Uncut[2]	Clearcuts[2]
		1	2	3	4	5		
Aspen leaves	4b	5b	85a	65a	90a	83a	4a	66b
Shrubs	19a	12a	26a	31a	32a	23a	19a	25a
Graminoids	45a	21b	45a	41a	47a	37a	45a	38a
Forbs	144b	81c	156b	167ab	177ab	229a	144a	162a
All plants	211b	118c	312a	305a	346a	372a	211a	291b

[1]*Within categories, values among years followed by the same letter are not significantly different (P = 0.05).*
[2]*Within categories, uncut and the mean value for clearcuts followed by the same letter are not significantly different (P = 0.05).*

Table 6.—*In vitro* digestibility (% dry matter) of understory vegetation on uncut and clearcut aspen blocks on Stoner Mesa, San Juan National Forest, July 1979

Category	Uncut	Years since logging[1]					Uncut[2]	Clearcuts[2]
		1	2	3	4	5		
Aspen leaves	45.6c	58.2a	55.1b	55.6b	56.0b	51.4c	45.6a	55.3b
Shrubs	53.9c	66.1a	59.2b	59.8b	54.4c	54.6c	53.9a	58.8b
Graminoids	61.8b	66.4a	68.1a	66.4a	66.2a	63.0b	61.8a	66.0b
Forbs	71.5a	73.1a	71.9a	72.9a	70.2a	70.9a	71.5a	71.8a

[1]*Within categories, values among years followed by the same letter are not significantly different (P = 0.05).*
[2]*Within categories, uncut and the mean value for clearcuts followed by the same letter are not significantly different (P = 0.05).*

Table 7.—Numbers of fecal groups per acre on uncut and clearcut aspen blocks on Stoner Mesa, San Juan National Forest, southwestern Colorado, 1979

Animal	Uncut	Years since logging[1]					Uncut[2]	Clearcuts[2]
		1	2	3	4	5		
Cattle	190b	145b	267b	509a	494a	534a	190a	390b
Deer	35b	94a	96a	106a	67ab	22b	35a	77b
Elk	7a	7a	10a	32a	30a	10a	7a	18a

[1]*Within species, values among years followed by the same letter are not significantly different (P = 0.05).*
[2]*Within species, uncut and the mean value for clearcuts followed by the same letter are not significantly different (P = 0.05).*

Figure 5.—Aspen sprouts in a fifth-year clearcut on Stoner Mesa study area.

The most obvious impact of logging on wildlife habitat was removal of the overstory, which adversely affected cavity-nesters and other species requiring a mature aspen forest. Clearcutting should have benefited species needing sparsely vegetated areas, at least initially, and those requiring tall, dense, shrub-like habitats that were provided by aspen sprouts in older blocks. Birds needing open foraging sites adjacent to standing timber also should have benefited from the cutting pattern employed. Although saleable logs were removed from the clearcuts, much more cover and possibly food was provided by logging slash in the clearcuts than by natural mortality in the adjacent forest.

The magnitude of feeding by wild herbivores was not quantitatively evaluated, but it was assumed from observations and pellet group counts that most of the feeding evidence resulted from cattle. A few deer and elk were present through the growing season, but the study area appeared to be used by these animals mainly during transit from summer to winter ranges.

Retention of a few large, windfirm trees per hectare would have been useful, especially in the larger clearcuts. Fewer skid trails might have produced less area of severely disturbed soil and provided fewer opportunities for livestock concentrations. Also, larger uncut buffers around water holes could have reduced trampling and compaction in nearby clearcuts.

In retrospect, from a wildlife habitat viewpoint, more benefits would probably have accrued if the timber sale had been extended over 10 years or more, or if several sales had been made over a longer period. These options would have produced newly-logged blocks each year, spaced over a wide area, which could have prolonged benefits to clearcut oriented species. However, such a pattern might have concentrated cattle on fewer areas and resulted in failure to regenerate the aspen.

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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**Rocky Mountain
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Experiment Station**

Fort Collins,
Colorado 80526

**Research Paper
RM-247**

Wounds and Decay in Residual Corkbark Fir

**Thomas E. Hinds, Robert E. Wood,
and Richard L. Bassett**

CLEMSON UNIVERSITY
JAN 9 1984
PUBLIC DOCUMENTS

Abstract

Decay associated with 11- to 17-year-old wounds on residual corkbark fir in the Apache-Sitgreaves National Forest in Arizona was analyzed. Over 95% of the open scars in different positions, sizes, and depth, and 86% of broken or dead tops were infected with decay fungi. Average volume of decay associated with open wounds was small (0.2 cubic feet) but increased with scar size class. *Amylostereum chailletii* and *Hematostereum sanguinolentum* were the most common trunk decayers, and *Fomitopsis annosa* and *Armillariella mellea* the common root rotters.

SDA Forest Service
search Paper RM-247

August 1983

Wounds and Decay in Residual Corkbark Fir

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Wounds and Decay in Residual Corkbark Fir

Thomas E. Hinds, Robert E. Wood, and Richard L. Bassett

Management Implications

Commercial spruce-fir stands occupy 635,000 acres in Arizona and New Mexico. Although Engelmann spruce (*Picea engelmannii* Parry), subalpine fir (*Abies lasiocarpa* var. *lasiocarpa* (Hook.) Nutt.), and corkbark fir (*A. lasiocarpa* var. *arizonica* (Merr.) Lem.) are characteristic of the type, Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), white fir (*A. concolor* (Gord. & Glend.) Lindl.), and aspen (*Populus tremuloides* Michx.) are fairly common associates. The true firs are gaining in importance for timber use, and they constitute nearly 3 billion board feet of the commercial sawtimber volume of the two states (Choate 1966, Spencer 1966). Past partial cutting in these stands has resulted in logging injuries to the residual trees. Injuries, particularly on nonresinous tree species such as corkbark fir, are common entrance points for decay fungi. Therefore, logging practices designed to protect future crop trees from wounding should be adopted.

Presale preparations to reduce tree injuries should include the following: (1) delay logging in the spring and early summer when the sap is flowing and the bark not tight; (2) lay out skid trails in advance of logging with no sharp turns and designate "bump trees" to be removed last; (3) mark the residual trees rather than trees to be cut; and (4) select appropriate size and type of logging equipment for the size of the residual trees and topography. Logging techniques would include the following: (1) limb, top, and cut trees into short logs prior to skidding to minimize injury to the residual stand; (2) cut stumps low in the skid trails; (3) fell trees either toward or away from skid trails; (4) use end-line skidding so that skidders can remain on the skid trails; and (5) gain the logging contractor's cooperation through training and supervision to convince him that much damage to residual trees is unnecessary and will not be tolerated. These guidelines have been recommended by Aho et al. (1983), and a slide-tape program is available to show how to minimize comparable logging injuries to residual trees in true fir stands in California (Aho et al. 1981). These guidelines can be adapted to the spruce-fir stands of Arizona and New Mexico. Using these methods and convincing the logger of their importance will lessen the decay losses in trees left for future harvest.

Introduction

Timber has been harvested in the spruce-fir and mixed conifer forests of the the Southwest for a number of years. Residual trees are often damaged during entries, but the significance of this damage, mainly trunk and root wounding, is unknown. The association of tree injuries and decay in some western true firs is well documented (Aho 1966, Aho 1977, Aho and Roth 1978, Hinds et al. 1960, Maloy and Gross 1963). The importance of logging wounds and associated decay in residual crop trees in intensively managed fir stands is being recognized, mainly in the Northwest (Aho 1960, Aho and Filip 1982, Aho et al. 1983, Parker and Johnson 1960, Wright and Isaac 1956). However, studies on the association of logging injuries and decay have not been made in the Southwest.

The objectives of this study were to determine (1) the influence of factors such as wound age, depth, position, and size on infection by decay fungi of wounds presumed to be old logging injuries; (2) the relative amounts of decay; and (3) the decay fungi associated with such scars. The study was limited to corkbark fir on the Alpine Ranger District of the Apache-Sitgreaves National Forest in Arizona, as previous observations indicated this species to be susceptible to wound infection following logging.

Methods

Four stands on the Alpine District were sampled: two along Double Cienega Creek in August 1979, and two along Corduroy Creek in June 1980. All stands had been logged 11 to 17 years earlier and were representative of the logged spruce-fir stands in the National Forest. Trees were selected, not randomly sampled, to give as large a sample of wounds of different types as possible. Broken and dead-top trees were common in the four stands. Since many of the wounds and damaged tops had occurred during the cutting period, it was assumed that most were logging injuries. Sample trees were felled and cut into 8- or 16-foot logs. Tree diameter at breast height (d.b.h.), height, age, and diameter inside bark (d.i.b.) for all cuts were recorded. Smalian's formula was used to calculate cubic foot volumes from a stump height of 1 foot to a 4-inch top d.i.b.

All wounds were classified according to their age, size, depth, and position on the tree. Scar area was

determined by multiplying the longest length by width of the open face inside the callus growth around the wound, and scar size was classified as follows:

Scar size class	Surface area square inches
1	<37
2	37–144
3	>144

Two depths were recognized: a scrape that did not damage the underlying wood was considered a bark wound; if the injury penetrated any noticeable part of the sapwood, it was considered a gouge wound. Wounds were classified as to their position on a tree: roots, ground-contact, basal, and upper-bole. The upper surfaces of all lateral roots were uncovered for a distance of 3 feet from the base of the sample trees and examined for root wounds and rot. Scars entirely below the ground were considered root wounds; those on the bole in contact with the ground, including those that extended onto roots, were classed as ground-contact wounds; those above ground line and below d.b.h. were classed as basal wounds; and those entirely above d.b.h. were classed as upper-bole wounds. Wounds completely callused over were considered healed.

Each scar was sectioned to determine the extent of stain or decay. Isolations were made from one or more stain or decay samples from each scar for identification of the decay fungi. Discoloration associated with incipient decay was considered active decay based upon the isolation and identification of a decay fungus. Stain and decay volume was computed by Smalian's formula. More than half of the injuries had less than 0.1 cubic foot of associated decay; however, the volumes were rounded off to the nearest 0.1 cubic foot in the final analysis.

Results

There were 152 scars and 23 dead or broken tops on the 53 trees examined, indicating that multiple injuries were common on individual trees. Scar ages ranged from 1 to 25 years; however, only 132 of those ranging from 11 to 17 years of age, the period of logging, and 21 dead or broken tops in the same age range were used in this analysis. The average scar age in this range was 13 years. Tree diameters ranged from 5.1 to 17.7 inches (average 11.0 inches), tree ages from 57 to 156 years (average 88 years), tree heights from 24 to 86 feet (average 60 feet), and individual gross tree volume from 1.0 to 63.7 cubic feet (average 18.9 cubic feet).

Because of the small sample size and nonrandom selection, the significance of the relationships between wound infection and volume loss to scar position, size, and depth was not tested. Consequently, only general trends can be interpreted from the data.

Wound infection.—Because of the high incidence of unhealed wounds infected by decay fungi (95%), differences between sampled stands can be considered insignificant. Infection decreased with increasing height above ground (table 1), from 100% in root and ground-contact scars to 86% in broken or dead tops (figs. 1, 2). Healed wounds were likewise more often infected when located in the basal portion of a tree (fig. 3).

The differences between scar sizes and incidence of infection were small (table 1). The confidence intervals ($P=0.05$) for scar size 1 and 2 were $\pm 5\%$ and $\pm 10\%$, respectively, indicating that wound size probably did not influence rate of infection. Wound depth probably does not influence infection, for gouge scars were 100% infected and bark scars $91 \pm 8\%$.

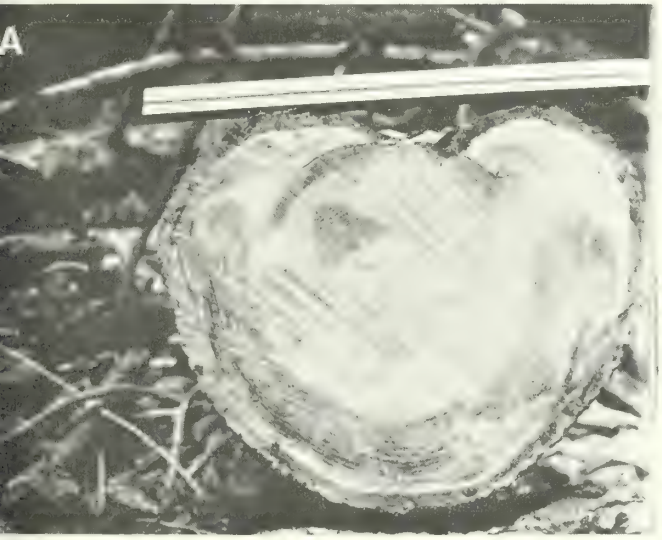
Decay associated with scars.—The average volume of decay per scar and the percentage of tree volume associated with the 11- to 17-year-old wounds is given in

Table 1.—Wound infection and decay in 11- to 17-year-old corkbark fir scars

Type of wound	Wounds	Infected	Average decay volume per scar	Average tree volume loss per scar
	number	*percent*	*cubic foot*	*percent*
Root	13	100	0.1	0.4
Ground contact	22	100	0.3	1.7
Basal	44	93	0.2	1.4
Basal—healed	8	63	<0.1	0.2
Upper bole	18	89	0.3	0.8
Upper bole—healed	27	33	<0.1	0.3
Broken top	14	86	0.5	2.1
Dead top	7	86	0.6	2.6
Scar size class (nonhealed)				
1	51	96	0.1	0.4
2	32	91	0.1	0.6
3	14	100	0.9	4.2
Wound depth (nonhealed)				
Gouge	42	100	0.2	1.2
Bark	55	91	0.2	1.0

able 1. The average cubic foot and percent volume loss er wound is based on the total number of scars involved. Loss per scar would be somewhat greater when nly infected scars are considered. The amount of decay ssociated with the various wounds varied from a trace, hat is, less than 0.1 cubic foot, to as much as 5.8 cubic eet in one tree that had a broken top.

In this study, 100% of the root and ground-contact cars and 93% of the basal scars were infected with ecay fungi which were causing tree volume losses 11 to 7 years after tree injury. Ground-contact scars and cars greater than 144 square inches in size resulted in he highest average tree volume loss, which amounted to .7% and 4.2%, respectively, of the gross tree volume. olume loss associated with root scars was smaller ecause the decay had to reach stump height before it aused measurable loss. Seventy-seven percent of the oot scars had less than 0.1 cubic foot associated butt ecay.



igure 1.—A. *Armillariella mellea* incipient decay (bottom) associated with 14-year-old root wound, and decay (top) associated with 14-year-old ground-contact wound. B. *Amylostereum chailletii* incipient decay (left section) 3 feet below 15-year-old dead top (right section) with advanced decay. Scale is 12 inches.

Figure 2.—A. Decay behind 14-year-old basal wound (left section) and 3 feet above wound (right section). B. Decay behind 14-year-old upper-bole wound. Scale is 12 inches.

The average volume loss for wound depth was the same for gouge and bark wounds (0.2 cubic foot), probably because the radial penetration of decay was similar. However, the radial penetration of decay and the volume loss did vary with scar size. The average radial penetration of decay associated with size 1, 2, and 3 scars was 1.0, 1.5, and 2.4 inches. The larger the scar, the greater the decay penetration and subsequent volume loss.

Fungi associated with scars.—Fifteen fungi were identified from decay associated with the wounds (table 2). Although only 86% of the infections were identified, they accounted for 97% of the decay volume. Of these fungi, only four appear to be important in number of infections and decay volumes. *Amylostereum chailletii* and *Hematostereum sanguinolentum* were found infecting most types of wounds and caused similar amounts of decay—an average of 0.3 cubic foot per infection. Both can cause a white pocket rot throughout a tree, and each caused about one-fourth of the total decay volume.

Fomitopsis annosa (= *Fomes annosus*) and *Armillariella mellea* were associated with root, ground-contact, and basal wounds. Although the average amount of decay associated with these infections was small (less than 0.3 cubic foot), the fungi are considered root pathogens commonly causing tree mortality. Forty-five percent of the 53 trees had root rots. Eight trees had 13 root wounds and associated decay in the butt log, and 16 other trees had one or more dead roots or roots containing decay. Root rot was associated with either ground-contact or basal wounds in 11 of these trees; consequently, it was impossible to determine whether or not the rot entered through the wound and was extending downward in the root or whether the rot was spreading upward into the wound in the butt. Of the 53 trees sampled, *F. annosa* was found on 15%; *A. mellea* on 28%; and both were present on 9%.

Of the scars considered noninfected by decay fungi, most had dried out and become case-hardened. *Ceratocystis piceae* (Munch) Bakshi and various unidentified species of *Leptographium*, *Graphium*, *Phialophora*, an *Verticicladiella* were isolated from stain behind thes scars, as well as from decay-infected scars.

Decay not associated with visible or detectabl wounds was found in 30% of the sample trees, and th amount of decay varied from a trace to 5.3 cubic feet i one tree with extensive heart rot. The decay average 0.5 cubic foot per infection. Fungi isolated from these in fections included *A. chailleti*, *A. mellea*, *Coniophorell olivacea*, *H. sanguinolentum*, *Polyporus tomentosus* va *circinatus* Satory et Marie, and *Phellinus nigrolimitatu* Most of these infections were root and butt rots.

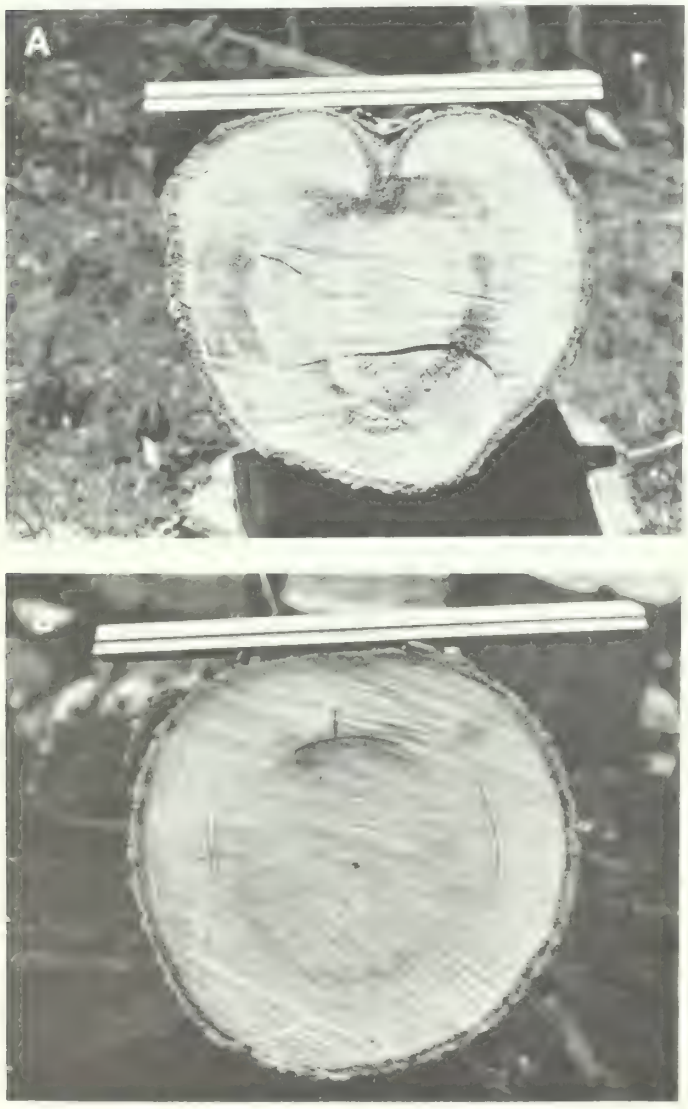


Figure 3.—A. Decay associated with 14-year-old healed basal wound. B. Incipient decay behind 17-year-old callused upper-bole wound. Scale is 12 inches.

Discussion

Although only minor amounts of decay were foun associated with the wounds on corkbark fir, it is impo tant that 95% of the unhealed scars examined were in fected. All basal wounds that extended to the groun line were infected, as were 93% of the unhealed wound in the lower portion of a butt log. This incidence of infe tion is similar to scar infection found by Parker an Johnson (1960) on 451 fifteen-year-old scars on balsar (alpine fir) (*Abies lasiocarpa* (Hook.) Nutt.) in the Princ George region of British Columbia. There, they found a basal wounds that extended to the ground infected, 92% of the butt scars infected, and 89% of broken tops in fected. They also found that each ground-contact, but and upper-bole scar resulted in an average loss of 1.5% of the tree volume 15 years after partial cutting. Th average loss for similar scars 11 to 17 years after pa tial cutting in this study of corkbark fir was 1.7% fo ground contact, 1.4% for basal, and 0.8% for upper bol scars, or an average of 1.3% for comparison purpose This loss is not as great as that associated with 8- an 13-year-old thinning wounds on red and white fir respectively, in northern California. There, Aho et a (1983) found that all wounds were infected by deca fungi which resulted in a loss of 1.9% of the gross me chantable cubic foot volume in red fir and 4.5% in whit fir.

Much of the decay associated with wounds was co sidered incipient; that is, the wood appeared to be firr but showed discoloration that did not extend more tha 3 or 4 feet above or below the scar. Decay loss assoc ated with most wounds was a rather small percentage o the total tree volume; however, if a tree has multipl wounds, and considering the increase in decay wit time, the loss can add up to a much higher percentage o a tree than indicated by the percentage of deca associated with a single scar. For example, the tota number of wounds per tree in this study, excluding dea or broken tops, and the total amount of associated deca were as follows:

Number of wounds	Number of trees	Percent decay
1	15	1.0
2	12	1.9
3	6	3.2
4	8	2.9
5–7	8	4.6

Table 2.—Fungi associated with 11- to 17-year-old wounds on corkbark fir

Fungi	Wounds								
	Root	Ground contact	Basal	Basal—healed	Upper bole	Upper bole—healed	Broken top	Dead top	Total infections
	number								percent
Amylostereum chailletii (Pers. ex Fr.) Boid.		3	8	2	3	8	2	4	24
Hematostereum sanguinolentum (Alb. et Schw. ex Fr.) Pouz.	1	3	9	1	1	1	6	1	18
Fomitopsis annosa (Fr.) Karst	1	6	5	1					10
Armillariella mellea (Vahl. ex Fr.)	8	2	1						9
Hirschioporus abietinus (Dicks. ex Fr.) Dorsk.			2		2			1	4
Coniophora arida (Fr.) Karst.		1	3	1					4
Coniophora puteana (Schum. ex Fr.) Karst		1	1						2
Coniophorella olivacea (Fr. ex Fr.) Karst.		1			2				2
Athelia bicolor (Pk.) Parm.		2	1						2
Flammula alnicola (Fr.) Kummer					2		1		2
Fomitopsis pinicola (Swartz ex Fr.) Karst.		1			1				2
Resinicium bicolor (Fr.) Kummer)	2								2
Peniophora septentrionalis Laurila			2						2
Pholiota squarrosa (Fr.) Kummer			2						2
Phellinus nigrolimitatus (Rohm.) Bourd. et Galz.		1							1
Unknown	1	2	7	0	5	0	3		14

A tree with any of the above number of wounds and a dead or broken top would likely sustain an additional 2 or 2.5% decay.

Although the volume loss associated with individual scars was small, and at first glance might be considered nearly insignificant, the volume loss associated with the particular part of a tree affected should not be overlooked. That is, the percentage of tree loss occurring with root, ground-contact, and basal scars should be approximately doubled for an estimate of loss in the butt log, as approximately one-half of the total tree volume is in the basal log in the residual trees. For instance, a 2% tree volume loss due to basal wounding would amount to approximately a 4% volume loss in the butt log. And, although a loss resulting from a broken or dead top was more than 2% of the total tree volume, the loss would be concentrated in the top log.

Many of the trees left after the first logging entry were too small for sawlog material, and one or more decades of growth will be required to attain sawlog size. Fungi already established in the wounds will increase defect or, perhaps, cause tree mortality. *Hematosterum sanguinolentum* is capable of rapid growth in other tree species. Davidson and Etheridge (1963) found that regardless of type of infection court in balsam fir (*Abies balsamea* (L.) (Mill.)) in natural stands in Quebec, decay developed at a fairly uniform linear rate of 0.3 to 0.4 foot per year. Injuries to the stem, including leaders, broken tops, and stem wounds, were almost twice as frequently infected as injured branches, and infection occurred only during the year following injury.

Inoculation studies by Whitney and Denyer (1970) showed that the average growth of *H. sanguinolentum* into balsam fir extended over an area of 65 square inches and a distance of 1.0 foot per year in infections that were 22 months old. Winter injuries were extremely susceptible to infection because of the competitive ability of the fungus to grow at low temperatures and the capacity of it to penetrate wood rapidly over a wide range of temperatures. Fruiting bodies of the fungus appeared on slash during July of the third year after felling. Spores were liberated during favorable conditions from April until the onset of freezing temperatures in October or November. Based on limited observations of corkbark fir in this study, the linear rate of spread of *H. sanguinolentum* decay behind 12 trunk scars amounted

to 0.3 ± 0.1 foot per year and 0.4 ± 0.2 foot per year in six broken tops. The rate of spread of 13 *A. chailletii* and 12 *F. annosus* infections was more erratic, being 0.4 ± 0.4 and 0.3 ± 0.3 foot per year, respectively.

Amylostereum chailletii was isolated from 50% and *H. sanguinolentum* from 37% of the scars on balsam fir in Quebec (Parker and Johnson 1960). They were associated with 24% and 18%, respectively, of the scars in this study of corkbark fir. While both fungi have been associated with similar infection courts in grand fir (*Abies grandis* (Dougl.) Lindl.) in the Blue Mountains of Oregon and Washington (Aho 1977), their frequency of occurrence was of minor importance. In subalpine fir (*A. lasiocarpa* (Hook.) Nutt.) in Colorado, *H. sanguinolentum* was the most important decay fungus and accounted for two-thirds of the trunk rot infections (Hinds et al. 1960). Both fungi appear to behave similarly on corkbark fir; however, their relative importance remains to be determined.

Other decay fungi isolated in this study are also known root rotters. *Phellinus nigrolimitatus* commonly causes root rot of grand fir (Miller and Partridge 1973) as does *P. tomentosus* (Aho 1977), *Resinicium bicolor* (= *Odontia bicolor*) (Nobles 1953), and *Flammula alnicola* (Denyer 1960, LaChance 1975). Infection can originate in the roots below ground and spread into active root tissue causing a white butt rot. Their role in causing tree decline or mortality is unknown.

The only brown rot fungi isolated were the two species of *Coniophora, Coniophorella,* and *Fomitopsis pinicola.* They are common in many conifers and are usually associated with various types of wounds, even root wounds. The other white rot fungi, *Hirschioporus abietinus, Pholiota squarrosa,* and *Athelia bicolor,* are also common. Decay caused by *Peniophora septentrionales* closely resembles that caused by *H. sanguinolentum,* and field identification made on the appearance of decay alone could be erroneous (Nobles 1956).

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Eighty-six percent of the broken or dead tops, and more than 95% of open scars in different positions, sizes, and depth, associated with 11- to 17-year-old wounds on residual corkbark fir contained decay. The average volume of decay was small. The common decay fungi were identified.

Keywords: *Abies lasiocarpa* var. *arizonica*, wounds, logging scars, decay fungi

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Research Paper
RM-248

Deer and Elk Forage Production in Arizona Mixed Conifer Forests

Ronald E. Thill, Peter F. Ffolliott, and
David R. Patton

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PUBLIC DOCUMENTS

Deer and Elk Forage Production in Arizona Mixed Conifer Forests

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Thill, Ronald E., Peter F. Ffolliott, and David R. Patton. 1983. Deer and elk forage production in Arizona mixed conifer forests. USDA Forest Service Research Paper RM-248, 13 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Mean forage production levels were closely associated with overstory basal area (BA), diminishing rapidly with increasing stand densities. Overstory-understory relationships were generally best described by log or log-log regression equations. Estimated total deer and elk forage on unlogged sites in mid-August is 82 pounds per acre (ovendry weight) at BA 50, versus 4 pounds per acre at BA 400. Expected forage production at BA 0 and 200 would vary from 118 to 5 pounds per acre, respectively, on a 2-year-old thinned site, compared with 448 to 16 pounds per acre on a 4-year-old thinned site. Eight and 16-year-old clearcuts produced 255 and 649 pounds per acre of potential forage, respectively. Forage benefits derived from clearcutting may be long-lived because of slow natural or artificial regeneration.

Keywords: Deer (*Odocoileus hemionus, O. virginianus*), elk (*Cervus elaphus*), forage production, mixed conifer forest

[1]*Research was supported by the USDA Forest Service, Rocky Mountain Forest and Range Experiment Station through its Wildlife Habitat Research Work Unit, Tempe, Ariz., and the School of Renewable Natural Resources, University of Arizona, Tucson. Station headquarters is in Fort Collins, in cooperation with Colorado State University.*

Deer and Elk Forage Production in Arizona Mixed Conifer Forests

Ronald E. Thill, Peter F. Ffolliott, and
David R. Patton

Management Implications

The National Forest Management Act requires National Forests to maintain minimum viable populations of all native wildlife species. Viable populations are a function of the quantity and quality of food and cover. Forage in the form of grass, forbs, and browse has been shown to be related to overstory characteristics and probably contributes more than other factors to the reproduction and maintenance of wild ungulate populations. Information that allows managers to predict understory production by different levels of basal area and treatment categories greatly facilitates the development of habitat capability coefficients. These coefficients are needed to meet the planning requirements of the National Forest Management Act. The regression equations we present for graminoids, forbs, and woody plants can be used as one part of a habitat capability coefficient for the mixed conifer forests of the Southwest.

Introduction

Inadequate nutrition has been suggested as a possible cause for relatively low fawn recruitment associated with declines in southwestern deer populations since the late 1950's (Schneegas and Bumstead 1977, Short 1979). Evidence suggests that quality and quantity of forage produced on summer range can directly influence productivity of deer herds in the West (Julander et al. 1961; Russo 1964; Hungerford 1970; Pederson and Harper 1978).

Together with associated grasslands and wet meadows, Arizona mixed conifer forests provide important summer range for mule deer (*Odocoileus hemionus*), whitetailed deer (*O. virginianus*), and elk (*Cervus elaphus*). Along with associated quaking aspen (*Populus tremuloides*) stands, Arizona's mixed conifer forests comprise 0.4% of the State's total area, but produce more than 6% of its water. More intensive management of these stands is likely because of increasing demands for water and other resources. The effects of this management on deer and elk forage supplies are unknown.

The objective of this study was to develop empirical regression equations to describe forest overstory-understory relationships in Arizona mixed conifer forests to predict potential deer and elk forage. Specifically, this paper reports findings on deer and elk forage production on unlogged, thinned, and clearcut sites, in the White Mountains of Arizona.

Study Areas

Southwestern mixed conifer forests occupy approximately 2.5 million acres in Arizona, New Mexico, and the San Juan Basin of southwestern Colorado (Jones 1974). In Arizona, this type is represented by about 300,000 acres of predominantly uncut, mixed-age stands composed of various combinations of Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), southwestern white pine (*P. strobiformis*), white fir (*Abies concolor*), corkbark fir (*A. lasiocarpa* var. *arizonica*), Engelmann spruce (*Picea engelmannii*), blue spruce (*P. pungens*), and quaking aspen (Embry and Gottfried 1971).

Data were obtained from seven mixed conifer sites on the Apache-Sitgreaves National Forest, Greenlee County, White Mountains, Arizona: North Thomas Creek, South Thomas Creek, West Willow Creek, East Willow Creek, Hannagan Creek, Bear Wallow, and Burro Creek. Data from the first three areas were combined and used to characterize unlogged, old-growth stands. Hannagan Creek and East Willow Creek were used to characterize 2- and 4-year-old thinned stands, respectively. Bear Wallow and Burro Mountain were sampled as 8- and 16-year-old clearcut sites, respectively.

Study area characteristics are summarized in table 1. Distribution of sampling points by aspect is shown because overstory and understory composition are often correlated with aspect (Thill 1981). East Willow Creek was thinned in 1972; sites sampled on Hannagan Creek were thinned in 1974. Logging on Burro Mountain and Bear Wallow was completed in 1959 and 1967, respectively. Logging slash on both clearcuts had been partially removed by broadcast burning. Destruction of advanced regeneration during logging and slash disposal, as well as subsequent regeneration failure, resulted in poor tree stocking on both clearcuts. The few small clumps of older regeneration which were present on these two sites were not sampled. Sampling points on both clearcuts predominantly faced south and southwest.

Annual precipitation at Thomas Creek from 1969 through 1974 averaged 27.0 inches; rainfall in 1975 and 1976 (the years of study) totaled 33.7 and 27.2 inches, respectively. May and June are the driest months, but summer thunderstorms from July through mid-September

Table 1.—Characteristics of mixed conifer sites sampled in the White Mountains of Arizona. Except for sample sizes by aspect, values are means with ranges in parentheses

Characteristic	Study area				
	Unlogged sites	Hannagan Creek	East Willow Creek	Bear Wallow	Burro Mountain
Basal area (ft^2/ac)	189 (50-450)	107 (0-275)	72 (0-300)	0	0
% Aspen	11.2 (0-100)	14.6 (0-100)	29.3 (0-100)		
% Spruce	12.1 (0-100)	14.1 (0-100)	14.6 (0-100)		
% Fir	20.4 (0-100)	9.3 (0-100)	7.5 (0-100)		
% Pine or Douglas-fir	56.6 (0-100)	59.3 (0-100)	23.2 (0-100)		
Elevation	8,874 (7,900-9,400)	8,687 (8,425-9,050)	9,080 (8,900-9,300)	8,800 (8,725-8,875)	9,550 (9,450-9,625)
Slope gradient	24.1 (0-60)	6.6 (0-25)	20.7 (0-40)	20.4 (0-45)	13.6 (0-30)
No. plots sampled by aspect: Total	379	75	142	54	73
North	46	5	17	-	-
Northeast	26	6	18	-	-
Northwest	49	-	11	-	-
South	33	12	12	20	38
Southeast	82	17	35	6	5
Southwest	39	4	-	28	30
East	80	10	34	-	-
West	24	3	15	-	-
Level	-	18	-	-	-

generally produce rain on 50% or more of the days. Summer nights are cool, and a few nights of below freezing temperatures often occur during May and June. Snow cover generally extends from November into April.

Study sites were confined to soils developed from basic basalt under cool, humid conditions. Sponseller was the predominant soil series (Leven and Stender 1967). These are moderately deep and deep, brownish-colored, noncalcareous, well-drained soils of gently-sloping high-elevation plateaus and steep mountains.

Field Methods

Current-year production of browse (leaves and stems 3/16-inch or less in diameter of all woody species except conifers) to a height of 5 feet was determined on 1/100-acre circular plots; herbage was measured on 9.6-square-foot circular plots. Data were collected at fixed intervals along randomly located transects oriented perpendicular to major drainages. Understory production estimates were determined using weight-estimate procedures (Blair 1959). Actual weights were determined at approximately one-seventh of the sampling points. Production was determined for each species encountered so that data could be partitioned int components having potential forage value for deer c elk. A minimum of 10 estimates and actual weights wer obtained for each forage species. Average moisture cor tent was determined for each species and was used t adjust data to an ovendry (122° F) basis. Overstory cor ditions at each plot were characterized by basal are estimates (square feet per acre) derived from poin sampling, utilizing a 25 basal area factor wedge prism Forested sites were sampled in 1976, clearcuts in 1975 Understory data were collected during August 13-26 i both years.

To quantify deer and elk forage production response to forest management practices, all plants were rated a either valuable or not valuable as potential forage fo deer and/or elk (table 2). Limited forage preference dat dealing specifically with southwestern mixed conife sites necessitated considerable reliance on food-habit literature from other western states. Ratings were fur ther substantiated by on-site observations and data col lected by Wallmo and McCulloch (1963) and Hungerfor (1970). Ratings for mule deer were based on work b Hungerford (1970), Kufeld et al. (1973), Neff (1974), an Urness et al. (1975). The source used for elk was Kufel (1973). Species rated as valuable generally correspon to Kufeld's (1973) "highly valuable" or "valuable categories. As such, these plants would be moderately t

highly preferred and would be expected to make up a moderate to major portion of the animals' diets, if encountered. Species rated in these references as valuable only during spring (March through May) or winter (December through February) were not classified as potential forages, because deer and elk use of the study area is normally restricted to a period from May to early October.

Table 2.—Woody and herbaceous plant species growing on logged and unlogged mixed conifer sites in Arizona which were rated as potentially valuable forage species for mule deer and/or elk

Botanical name[1]	Common name	Deer[2]	Elk[2]
Woody Plants			
Acer glabrum Torr.	Rocky Mountain maple	*	*
Amelanchier spp.	serviceberry	*	
Berberis repens Lindl.	creeping mahonia	*	*
Ceanothus fendleri Gray	Fendler ceanothus	*	
Lonicera arizonica Rehd.	Arizona honeysuckle	*	*
Lonicera utahensis Wats.	Utah honeysuckle		*
Pachystima myrsinites (Pursh.) Raf.	myrtle pachistima	*	*
Populus tremuloides Michx.	quaking aspen	*	*
Quercus gambelii Nutt.	Gambel oak	*	*
Ribes pinetorum Greene	orange gooseberry		*
Rosa arizonica Rydb.	Arizona rose		*
Robinia neomexicana Gray	New Mexico locust	*	
Rubus parviflorus Nutt.	western thimbleberry	*	*
Rubus strigosus Michx.	red raspberry	*	
Sambucus spp.	elderberry	*	*
Salix scouleriana Barratt	Scouler willow	*	*
Symphoricarpos oreophilus Gray	mountain snowberry	*	*
Vaccinium myrtillus L.	Rocky Mountain whortleberry		*
Forbs			
Achillea lanulosa Nutt.	western yarrow	*	
Actaea rubra (Ait.) Willd.	red baneberry	*	
Aster foliaceus Lindl.	leafybract aster	*	
Cirsium parryi (Gray) Petrak	thistle		*
Cirsium pulchellum (Greene) Woot. and Standl.	thistle		*
Epilobium angustifolium L.	fireweed	*	*
Erigeron flagellaris Gray	trailing fleabane	*	
Geranium caespitosum James	purple geranium		*
Geranium richardsonii Fisch. and Trautv.	Richardson geranium	*	*
Hieracium fendleri Schultz Bip.	hawkweed	*	
Houstonia wrightii Gray	Wrights bluets	*	
Ligusticum porteri Coult. and Rose	Porter ligusticum	*	
Lupinus argenteus Pursh.	silvery lupine	*	*
Osmorhiza depauperata Phil.	bluntseed sweetroot	*	
Phacelia magellanica (Lam.) Coville	phacelia	*	*
Polygonum aviculare L.	prostrate knotweed	*	*
Potentilla hippiana Lehm.	horse cinquefoil		*
Potentilla thurberi Gray	Thurber cinquefoil		*
Pseudocymopterus montanus (Gray) Coult. and Rose	pseudocymopterus	*	
Senecio bigelovii Gray	Bigelow groundsel		*
Silene scouleri	Scouler silene	*	
Smilacina racemosa (L.) Desf.	feather solomonplume	*	*
Swertia radiata (Kellogg) Kuntze	deer ears	*	
Taraxacum officinale Weber	common dandelion	*	*
Thalictrum fendleri Gray	Fendler meadow-rue	*	
Trifolium pinetorum Greene	clover	*	
Vicia americana Muhl.	American vetch	*	*
Vicia pulchella H.B.K.	sweetclover vetch	*	*
Viquiera multiflora (Nutt.) Blake	showy goldeneye	*	

Table 2.—continued

Table 2.—Woody and herbaceous plant species growing on logged and unlogged mixed conifer sites in Arizona which were rated as potentially valuable forage species for mule deer and/or elk—(Continued)

Botanical name[1]	Common name	Deer[2]	Elk[2]
Graminoids			
Agrostis alba L.	redtop		*
Agropyron desertorum (Fisch). Schult.	crested wheatgrass	*	
Agropyron smithii Rydb.	bluestem wheatgrass		*
Agropyron subsecundum (Link) Hitchc.	bearded wheatgrass		*
Bromus inermis Leyss.	smooth brome	*	*
Dactylis glomerata L.	orchardgrass	*	*
Festuca arizonica Vasey	Arizona fescue	*	
Koeleria cristata Pers.	prairie junegrass	*	*
Muhlenbergia montana (Nutt). Hitchc.	mountain muhly	*	
Muhlenbergia virescens (H.B.K.) Kunth	screwleaf muhly		*
Panicum bulbosum H.B.K.	bulb panicum		*
Phleum pratense L.	timothy		*
Poa fendleriana (Steud.) Vasey	mutton bluegrass	*	*
Poa pratensis L.	Kentucky bluegrass	*	*
Sitanion hystrix (Nutt.) J. G. Sm.	bottle brush	*	

[1]*Scientific and common names follow Nickerson, Brink, and Feddema (1976); they follow Kearney and Peebles (1960) and Kelsey and Dayton (1942) if not listed by Nickerson et al.*
[2]*Asterisks denote species of potential forage value to deer or elk during summer or fall.*

Analytic Methods

Weighted regression procedures were used to predict understory (forb, graminoid, and woody plant) production and production of deer and elk forage (herbage, browse, and total forage) using basal area as the independent variable. Total basal area was regressed with mean production values associated with 25 square feet basal area increment. Where observations are means, as is the case here, the inverse of the variance of the mean is an appropriate weighting factor, particularly where sample sizes vary considerably for each level of the independent variable (Steel and Torrie 1960). Thus, the factor used to weight each production value was:

$$w_i = n_i/s_i^2$$

where n_i and s_i^2 are the sample size and variance, respectively, associated with each mean.

Of the following models which were screened, only the one with the highest r-value is presented: $Y = f(X)$, $Y = f(LgX)$, $LgY = (X)$, $LgY = f(LgX)$, $Y = f(1/X)$; Lg denotes a common log to base 10 transformation. One was added to all values prior to logarithmic transformation.

Procedures outlined by Meyer (1942) and exemplified by Clary and Ffolliott (1966) were used to test for differences in production of understory components between weighted regression curves developed for unlogged and thinned stands. The jackknife procedure was used to estimate a variance of the estimate for each basal value used in the comparison tests (Mosteller and Tukey 1977). Comparisons between the unlogged treatment and each of the thinned sites were made from basal area (BA) 50 (the lowest BA sampled on the unlogged sites) to 225 (the highest BA on Hannagan Creek and Willow Creek for which at least two plots were inventoried). East Willow Creek and Hannagan Creek were compared from BA 0 through BA 225. Production differences were tested at 25-square-foot increments (i.e., BA 0, 25, 50, . . .). All tests of significance were at the 0.05 level.

Results

Unlogged Sites

Weighted regressions of means of understory production components with total basal area yielded an average r^2 of 0.71 for those relationships having significant regression coefficients; r^2 values ranged from 0.18 for forbs (Y2) to 0.86 for total understory production (Y4) (table 3). Log and log-log functions produced highest r values for all understory components except forbs. The linear model yielded the highest r^2 for forbs. None of the models tested yielded significant ($P > 0.05$) regression coefficients for deer and elk browse components (i.e. Y6, Y9, and Y12).

Graminoids (Y1) were a minor understory component except in fairly open stands. At BA 100 or higher, less than 35 pounds per acre of graminoids would be expected, as compared to about 125 pounds per acre at BA 50. Forbs (Y2) were the most important understory component for all basal area levels higher than about 85, but were out-produced by graminoids below this BA level.

The regression line for woody plants production (Y3) was nearly linear, with production increasing only slightly with decreasing stand density; at the lowest basal area sampled (BA 50), less than 15 pounds per acre would be expected.

Predicted levels of total understory production and various deer and elk forage components at selected basal area levels are presented in table 4. Predicted total understory production (Y4) would range from a low of 35 pounds per acre at BA 400 to a high of about 140 pounds per acre at BA 50. As indicated in this table, not only does total understory production rapidly decline with increasing stand density, but the percentage of this total having potential value to deer and elk also rapidly declines with increasing density. For example, potential elk forage (Y10) as a percent of total understory production (Y4) decreases from 39% at BA 50 to 11% at BA 400.

Unlogged stands produced somewhat greater quantities of elk forage than deer forage at lower stand densities, but approximately equal amounts for both animals at higher stand densities (table 4). At BA 50, 28%, 39%, and 58% of total understory production would consist of deer, elk, and deer or elk forage, respectively. Potential deer forage (Y7) would consist of about one-third herbage (Y5) and two-thirds browse (Y6) throughout the range of stand densities sampled. Elk forage (Y10) would consist primarily of herbage (Y8) at lower basal area levels, and equal amounts of herbage and browse at BA 400. Total production of species having potential value to either deer or elk (Y13) would comprise 58% of total understory production at BA 50, compared with 11% at BA 400.

Few forage species were encountered on plots with the highest basal area (table 5). For example, 94% of the total deer and elk forage (Y13) for plots with BA 375 through 400 was produced by 4 species, while 11 species produced 97% at BA 50 to 75. Although grasses were a minor understory component (except under lower stand densities), they were the principal forages under low, medium, and high basal area levels (table 5).

Thinned Sites

For the 2-year-old thinning on Hannagan Creek, logarithmic function produced highest r^2 values when means of understory components were regressed with BA (table 3). Value of r^2 ranged from 0.51 for deer herb-

Table 3.—Weighted regression equations of mean understory production components with basal area (X) for unlogged and thinned mixed conifer sites in the White Mountains of Arizona

Stand condition	Vegetation group[1]	Regression equation	SEE	r^2
Unlogged	Graminoids	Lg(Y1) = 5.471 - 1.974 Lg(X)	.060	.81
	Forbs	Y2 = 47.50 - 0.039 (X)	1.05	.18
	Woody plants	Y3 = 36.64 - 13.91 Lg(X)	.840	.84
	Total understory prod.	Lg(Y4) = 3.299 - .6693 Lg(X)	.005	.86
	Herbage for deer	Lg(Y5) = 2.797 - .9774 Lg(X)	.105	.58
	Total deer forage	Lg(Y7) = 3.643 - 1.189 Lg(X)	.040	.83
	Herbage for elk	Lg(Y8) = 3.995 - 1.348 Lg(X)	.045	.72
	Total elk forage	Lg(Y10) = 3.764 - 1.178 Lg(X)	.030	.77
	Deer and elk herbage	Lg(Y11) = 4.120 - 1.396 Lg(X)	.045	.71
	Total deer and elk forage	Lg(Y13) = 4.259 - 1.370 Lg(X)	.030	.82
Thinned 2 years prior	Graminoids	Y1 = 55.55 - 23.63 Lg(X)	2.19	.55
	Forbs	Y2 = 331.1 - 136.3 Lg(X)	1.39	.92
	Woody plants	Lg(Y3) = 1.163 - .0034 (X)	.080	.86
	Total understory prod.	Y4 = 407.2 - 166.4 Lg(X)	1.68	.99
	Herbage for deer	Y5 = 51.00 - 22.66 Lg(X)	3.65	.51
	Total deer forage	Y7 = 80.39 - 33.41 Lg(X)	2.78	.72
	Herbage for elk	Y8 = 77.57 - 33.15 Lg(X)	2.68	.68
	Total elk forage	Y10 = 107.1 - 44.20 Lg(X)	2.19	.77
	Deer and elk herbage	Y11 = 90.64 - 38.85 Lg(X)	3.29	.65
	Total deer and elk forage	Y13 = 118.0 - 48.98 Lg(X)	2.58	.75
Thinned 4 years prior	Graminoids	Y1 = 296.6 - 122.6 Lg(X)	3.35	.39
	Forbs	Y2 = 247.6 - 104.7 Lg(X)	2.83	.64
	Woody plants	Lg(Y3) = 2.020 - .5962 Lg(X)	.070	.50
	Total understory prod.	Y4 = 663.6 - 279.1 Lg(X)	2.55	.82
	Herbage for deer	Y5 = 211.9 - 89.50 Lg(X)	2.24	.68
	Total deer forage	Y7 = 373.6 - 156.0 Lg(X)	1.70	.89
	Herbage for elk	Lg(Y8) = 2.181 - .0093 (X)	.064	.99
	Total elk forage	Y10 = 397.2 - 166.8 Lg(X)	2.36	.83
	Deer and elk herbage	Y11 = 234.8 - 99.28 Lg(X)	2.60	.62
	Total deer and elk forage	Y13 = 448.2 - 187.8 Lg(X)	2.10	.85

[1]*Regression coefficients for deer and elk browse components (i.e., Y6, Y9, and Y12) were not significant at the 0.05 level.*

Table 4.—Predicted amounts (pounds per acre) of total understory production and various deer and elk forage components at selected basal area levels for unlogged mixed conifer sites[1]

Vegetation group	Basal area			
	50	100	200	400
Total production Y4	142	90	56	35
Deer herbage Y5	12 (8)[2]	6 (7)	3 (5)	1 (3)
Deer browse Y6	28 (20)	11 (12)	4 (7)	2 (6)
Total deer forage Y7	40 (28)	17 (19)	7 (13)	3 (9)
Elk herbage Y8	48 (34)	19 (21)	7 (13)	2 (6)
Elk browse Y9	8 (6)	5 (6)	3 (5)	2 (6)
Total elk forage Y10	56 (39)	24 (27)	10 (18)	4 (11)
Deer or elk herbage Y11	53 (37)	20 (22)	7 (13)	2 (6)
Deer or elk browse Y12	29 (20)	12 (13)	5 (9)	2 (6)
Total deer or elk forage Y13	82 (58)	32 (36)	12 (21)	4 (11)

[1] *Values for herbage and total forage categories were obtained from weighted regression equations presented in Table 3; browse values were obtained by subtraction.*

[2] *Values in parentheses indicate the percent that the preceding value is of total understory production (Y4). All values rounded to nearest whole number.*

Table 5.—Principal deer and elk forage species present at low, medium, and high basal area classes on unlogged mixed conifer sites[1]

Basal area class (ft²/ac)		
50-75 (n = 33)	225 (n = 31)	375-400 (n = 10)
Muhlenbergia virescens (30)	*Muhlenbergia virescens* (28)	*Bromus inermis* (41)
Muhlenbergia montana (20)	*Lupinus argenteus* (15)	*Geranium richardsonii* (24)
Robinia neomexicana (11)	*Pachystima myrsinites* (11)	*Populus tremuloides* (23)
Bromus inermis (8)	*Bromus inermis* (7)	*Pseudocymopterus montanus* (6)
Quercus gambelii (7)	*Quercus gambelii* (6)	
Vicia americana (6)	*Populus tremuloides* (5)	
Pachystima myrsinites (5)	*Koeleria cristata* (4)	
Geranium richardsonii (3)	*Robinia neomexicana* (4)	
Lupinus argenteus (3)	*Senecio bigelovii* (4)	
Populus tremuloides (2)	*Geranium richardsonii* (3)	
Sitanion hystrix (2)	*Thalictrum fendleri* (3)	
	Achillea lanulosa (3)	

[1] *Only species making up >0.5 percent of total understory production (Y4) within the indicated basal area classes are listed. Values in parentheses indicate percent of total deer and elk forage (Y13), rounded to nearest whole number.*

age (Y5) to 0.99 for total understory production (Y4), and averaged 0.74 for all forage components on Hannagan Creek. None of five models tested provided significant regression coefficients for deer and elk browse variables Y6, Y9, and Y12. Predicted total understory production (Y4) would range from 15 pounds per acre at BA 225 to 407 pounds per acre at BA 0. Forbs were the dominant understory component at all basal area levels. Maximum browse production was 14 pounds per acre at BA 0. Graminoids were a minor understory component except at low stand densities.

Predicted levels of total understory production (Y4) and deer and elk forage at selected BA levels are presented in table 6. Unlike unlogged stands (but like the 4-year-old East Willow Creek thinning), that portion of total understory production which consisted of deer (Y7) and elk (Y10) forage remained fairly constant with increasing stand density. As with East Willow Creek 4 years after logging, similar 2-year-old thinned stands would be expected to produce approximately equal amounts of deer (Y7) and elk (Y10) forage throughout the range of basal area sampled. Total forage potentially useful to deer or elk would be about 29% of total understory production (Y4) at BA 0 versus 21% at BA 200.

For the 4-year-old thinning on East Willow Creek, logarithmic functions produced highest r^2 values for all significant relationships when means of understory production components were regressed with basal area. Values of r^2 ranged from 0.39 for graminoids (Y1) to 0.99

or elk herbage (Y8), and averaged 0.72. None of the models produced significant regression coefficients for deer and elk browse components.

Graminoid production (Y1) would vary from 8 pounds per acre at BA 225 to 300 pounds per acre at BA 0. Like unlogged stands, browse production was inversely related to basal area, and increased only slightly with decreasing stand density to a maximum of 104 pounds per acre at BA 0. Predicted total understory production (Y4) would range from a low of 6 pounds per acre at BA 225 to a high of 663 pounds per acre at BA 0.

In contrast to unlogged sites, deer and elk forage (Y7, Y10, and Y13) as a percent of total production (Y4), remained fairly constant with increasing basal area (table 5). Thus, although less vegetation is present at higher basal area levels, more of what is present is potentially useful deer and elk forage. Data in table 6 suggest that similar 4-year-old thinned stands would produce somewhat more deer herbage (Y5) than elk herbage (Y8), but approximately equal amounts of total deer (Y7) and elk (Y10) forage at similar basal levels throughout the range of stand densities sampled.

As with unlogged sites, fewer forage species were encountered on higher than lower basal area plots on both thinned sites (tables 7 and 8). Grasses dominated deer and elk forage production at the lowest basal area classes on both thinned sites, but quaking aspen dominated at intermediate and high basal area levels (tables 7 and 8).

Comparisons Among Sites

Basal area levels at which significant differences ($P < 0.05$) were detected in predicted yields of various understory vegetation groups, when weighted regression curves developed for the unlogged, and the 2- and 4-year-old sites were compared, are summarized in table 9. The 4-year-old thinning produced significantly greater amounts of forbs (Y2), total understory production (Y4), and deer and elk forage (Y7, Y10, and Y13) than unlogged sites under certain basal area levels. Forb production (Y2) at BA 50 was greater on the 2-year-old thinning than on unlogged sites, but unlogged stands produced more total deer and elk forage (Y13) under low basal area conditions. Production of 8 of the 10 understory components was significantly greater on the 4- than the 2-year-old thinning, especially under lower stand densities. A graphic comparison of differences in total understory production and total deer and elk forage for unlogged and thinned stands is shown in figure 1.

Clearcut Sites

Total herbage and browse production on the 16-year-old clearcut (Burro Mountain) was nearly twice that of the 8-year-old clearcut (Bear Wallow) (table 10). Forbs were the dominant vegetative component on the younger clearcut, but graminoids and forbs were equally impor-

Table 6.—Predicted amounts (pounds per acre) of total understory production and various deer and elk forage components at selected basal area levels for two mixed conifer sites thinned 2 (Hannagan Creek) and 4 years (East Willow Creek) earlier[1]

Site	Vegetation group	Basal area (ft^2/ac) 0	50	100	200
Hannagan Creek	Total production Y4	407	123	74	24
	Deer herbage Y5	51 (13)[2]	12 (10)	6 (8)	0
	Deer browse Y6	29 (7)	11 (9)	7 (9)	3 (13)
	Total deer forage Y7	80 (20)	23 (19)	13 (18)	3 (13)
	Elk herbage Y8	78 (19)	21 (17)	11 (15)	1 (4)
	Elk browse Y9	29 (7)	11 (9)	8 (11)	4 (17)
	Total elk forage Y10	107 (26)	32 (26)	19 (26)	5 (21)
	Deer or elk herbage Y11	91 (22)	24 (20)	13 (18)	1 (4)
	Deer or elk browse Y12	27 (7)	10 (8)	7 (9)	4 (17)
	Total deer or elk forage Y13	118 (29)	34 (28)	20 (27)	5 (21)
East Willow Creek	Total production Y4	664	187	104	21
	Deer herbage Y5	212 (32)	59 (32)	33 (32)	6 (29)
	Deer browse Y6	162 (24)	48 (26)	28 (27)	8 (38)
	Total deer forage Y7	374 (56)	107 (57)	61 (59)	14 (67)
	Elk herbage Y8	151 (23)	51 (27)	17 (16)	1 (5)
	Elk browse Y9	246 (37)	61 (33)	46 (44)	12 (57)
	Total elk forage Y10	397 (60)	112 (60)	63 (60)	13 (62)
	Deer or elk herbage Y11	235 (35)	65 (35)	36 (35)	6 (29)
	Deer or elk browse Y12	213 (32)	63 (34)	36 (35)	10 (48)
	Total deer or elk forage Y13	448 (67)	128 (68)	72 (69)	16 (76)

[1] *Values for herbage and total forage categories were obtained from weighted regression equations presented in Table 3; browse values were obtained by subtraction.*

[2] *Values in parentheses indicate the percent that the preceding value is of total understory production (Y4) for respective site. All values rounded to nearest whole number.*

Table 7.—Principal deer and elk forage species present at low, medium, and high basal area classes on Hannagan Creek 2 years after logging[1]

Basal area class (ft²/ac)					
0-25 (n = 10)		100-125 (n = 22)		200-225 (n = 6)	
Sitanion hystrix	(41)	*Populus tremuloides*	(50)	*Populus tremuloides*	(74)
Koeleria cristata	(25)	*Koeleria cristata*	(24)	*Muhlenbergia virescens*	(18)
Phacelia magellanica	(12)	*Geranium richardsonii*	(9)	*Bromus inermis*	(6)
Populus tremuloides	(10)	*Bromus inermis*	(7)		
Bromus inermis	(6)	*Phacelia magellanica*	(6)		
Robinia neomexicana	(3)				
Geranium richardsonii	(2)				
Achillea lanulosa	(2)				

[1]*Only species making up >0.5 percent of total understory production (Y4) within the indicated basal area classes are listed. Values in parentheses indicate percent of total deer and elk forage (Y13), rounded to nearest whole number.*

Table 8—Principal deer and elk forage species present at low, medium, and high basal area classes on East Willow Creek 4 years after logging[1]

Basal area class (ft²/ac)					
0-25 (n = 62)		125 (n = 8)		225-250 (n = 7)	
Bromus inermis	(39)	*Populus tremuloides*	(68)	*Populus tremuloides*	(56)
Phacelia magellanica	(15)	*Bromus inermis*	(16)	*Bromus inermis*	(20)
Populus tremuloides	(13)	*Geranium richardsonii*	(4)	*Vaccinium myrtillus*	(20)
Sitanion hystrix	(10)	*Phacelia magellanica*	(4)	*Erigeron flagellaris*	(3)
Geranium richardsonii	(5)	*Erigeron flagellaris*	(3)	*Pseudocymopterus montanus*	(1)
Koeleria cristata	(3)	*Lupinus argenteus*	(2)	*Rubus parviflorus*	(1)
Lupinus argenteus	(3)	*Vaccinium myrtillus*	(1)		
Achillea lanulosa	(3)	*Pseudocymopterus montanus*	(1)		
Erigeron flagellaris	(2)				
Vicia americana	(2)				
Dactylis glomerata	(1)				
Ribes pinetorum	(1)				
Cirsium spp.	(1)				
Phleum pratense	(1)				

[1]*Only species making up >0.5 percent of total understory production (Y4) within the indicated basal area classes are listed. Values in parentheses indicate percent of total deer and elk forage (Y13), rounded to nearest whole number.*

tant on Burro Mountain. Sedges (*Carex* spp.) comprised 18.3% and 25.9% of the graminoid production on Bear Wallow and Burro Mountain, respectively. Browse production was negligible on both clearcuts. In addition to higher total production, Burro Mountain also produced a greater proportion (56.1% versus 33.9%) of forage having potential forage value to deer and elk (table 10). Production of potential elk forage was somewhat higher than deer forage on both clearcuts. The contribution of principal deer and elk forage species to total production is summarized in table 11.

Expected understory production for plots with less than 25 square feet per acre of basal area for Hannagan Creek and East Willow Creek (from equations in table 3) and actual production values from Bear Wallow and Burro Mountain are plotted against time since logging (fig. 2). Judging from these limited data, the following general trends are suggested:

1. Forb production may have already peaked by age 16.
2. Browse production peaked shortly after logging.
3. Graminoid production may still increase for several years beyond age 16.
4. Peak total production, consequently, may be several years into the future.

Discussion

With regard to successional patterns on clearcuts Basile and Jensen (1971) observed similar forb and

Table 9.—Basal area levels at which significant differences ($P < 0.05$) were detected in predicted yields of understory vegetation groups when weighted regression curves developed for the three timbered treatments were compared at selected basal area levels

Vegetation group[2]		Treatments compared and basal area ranges tested[1]		
		UMC vs EWC BA 50-225	UMC vs HC BA 50-225	EWC vs HC BA 0-225
Graminoids	Y1			0[b]
Forbs	Y2	50-75[b]	50[c]	
Woody plants	Y3			0[b]
Total production	Y4	50-75[b]		0-50[b]
Deer herbage	Y5			
Total deer forage	Y7	50-150[b]		0-75[b]
Elk herbage	Y8			0[b]
Total elk forage	Y10	50-175[b]		0-175[b]
Deer or elk herbage	Y11			0[b]
Total deer or elk forage	Y13	50-175[b]	50-75[a]	0-175[b]

[1] *Where differences are significant, the treatment with the higher production in each comparison is indicated by the following superscripts: a = unlogged mixed conifer sites (UMC); b = East Willow Creek (EWC); and c = Hannagan Creek (HC).*

[2] *Weighted regression coefficients for deer and elk browse variables Y6, Y9, and Y12 were not significant.*

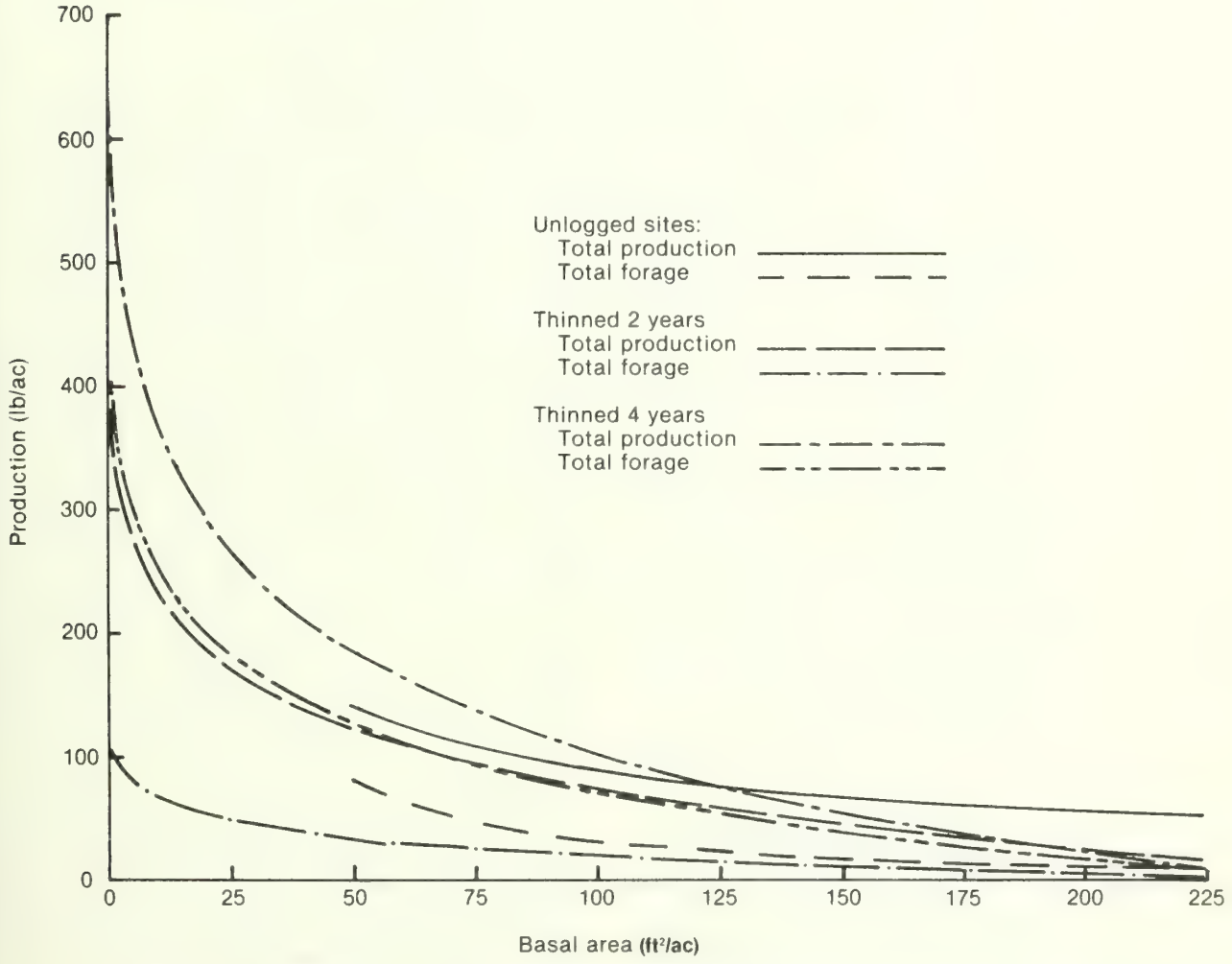

Figure 1.—Comparison of total understory production (Y4) and total deer and elk forage production (Y13) on unlogged and thinned mixed conifer sites, White Mountains, Arizona.

Table 10.—Herbage and browse production on two mixed conifer sites clearcut 8 (Bear Wallow) and 16 years (Burro Mountain) prior to 1975 inventory listed by plant groups and by forage components potentially useful to deer and elk

Vegetation group	Bear Wallow pounds per acre	Bear Wallow %	Burro Mountain pounds per acre	Burro Mountain %
Total production				
Graminoids	183	24.3	533	46.0
Forbs	535	71.1	615	53.1
Woody plants	34	4.5	10	0.9
Total	752	99.9	1158	100.0
Deer forage[1]				
Herbage	151	20.1	371	32.0
Browse	16	2.1	3	0.3
Total	167	22.2	374	32.3
Elk forage				
Herbage	206	27.4	393	33.9
Browse	12	1.6	8	0.7
Total	218	29.0	401	34.6
Deer and elk forage				
Herbage	234	31.1	639	55.2
Browse	21	2.8	10	0.9
Total	255	33.9	649	56.1

[1]*Percentage values from here down are percent of total production values from preceding line.*

Table 11.—Principal deer and/or elk forage species on Bear Wallow and Burro Mountain clearcuts as a percent by weight of total production

Species	Bear Wallow	Burro Mountain
Woody plants		
Ribes pinetorum	1.4	0.7
Rubus strigosus	1.1	0.2
Subtotal	2.5	0.9
Grasses		
Bromus inermis	11.2	7.3
Dactylis glomerata	1.9	0.0
Festuca arizonica	0.0	15.6
Koeleria cristata	0.0	1.4
Muhlenbergia montana	0.0	1.7
Phleum pratense	2.4	0.0
Poa fendleriana	1.2	tr
Sitanion hystrix	1.6	3.0
Subtotal	18.3	29.0
Forbs		
Achillea lanulosa	0.5	3.3
Cirsium parryi	0.0	10.6
Phacelia magellanica	2.2	0.7
Subtotal	2.7	14.6
Total	23.5	44.5

graminoid production trends on clearcut lodgepole pine sites in Montana. They found that production of the dominant forb class peaked at 10 years, while graminoid production peaked at about 2 to 3 years later. Browse was also the least productive class initially, but (unlike here) continually increased and exceeded production of each of the other classes at about 14 years after clearcutting.

In mixed conifer stands, between 7,000 and 9,000 fee elevation, in southern New Mexico, Hanks and Dick Peddie (1974) found that a dominant forb stage wa typically followed by a second stage dominated b Gambel oak (*Quercus gambelii*) and locust (*Robini neomexicana*) along with several other deciduou shrubs. Moir and Ludwig (1979) also described severa mixed conifer habitat types having a more productiv

Figure 2.—Trends in understory production for thinned sites with less than 25 ft² of basal area (ages 2 and 4) and for clearcut mixed conifer sites as affected by time.

shrub component than those sampled in this study. In searching for suitable clearcut sites, several sites were observed which had developed relatively dense stands of locust, raspberry (*Rubus* spp.), and gooseberry (*Ribes* spp.). However, except for a few isolated concentrations of Gambel oak and locust (particularly on portions of the South Fork of Thomas Creek), these species were not a major understory component on any of the forested areas sampled. Where Gambel oak and locust were present on unlogged sites, they generally had grown beyond the reach of deer and elk. Given the relative scarcity of these species on unlogged and thinned sampling areas, it was felt that these species probably would not be a major successional component if these areas had been clearcut. Consequently, the two clearcuts which were sampled were selected as being representative of how these particular forest sites might respond to clearcutting.

In addition to the influence of habitat types on occurrence of a dominant shrub stage, extent of site disturbance and inherent soil moisture conditions may also be important. On logged and burned Douglas-fir sites in Oregon, Dyrness (1973) only observed a dominant shrub stage on the more heavily burned, drier sites. However, on more moist, less disturbed sites he suggested that succession would proceed from a mixture of ferns, herbs, and low shrubs directly to trees. Most of the shrub-dominated clearcuts observed in this study appeared to be fairly wet sites having shallow, rocky soils.

Deer and elk also may have had some influence on initial shrub abundance and vigor, at least on Burro Mountain. Jones (1967) indicated that both animals were numerous on this area and caused serious browsing damage to planted ponderosa pine shortly after logging and pine planting.

An invasion of conifers (with or without aspen) initiates the final successional stage on mixed conifer sites. However, substantial natural regeneration often requires 50 to 100 years, especially where dense stands of grasses and forbs develop (Stahelin 1943, Hanks and Dick-Peddie 1974). Given their inherent productivity, long life, and abundance of desirable deer and elk forage, it would appear that mixed conifer clearcuts (at least those on predominantly south and southwest aspects) provide a valuable long-term forage resource for both deer and elk.

Unlogged mixed conifer forests produce little understory even under basal area levels as low as 50 square feet per acre. At BA 189 (the overall mean for unlogged sites), predicted total production of deer and elk forage would be about 13 pounds per acre. At 4 years after thinning, East Willow Creek produced significantly greater amounts of deer and elk forage (Y13) for BA 50 through 175 than unlogged sites. Furthermore, these increases in forage after thinning were accompanied by a gradual increase in deer and elk use as indexed by accumulated pellet groups (Patton 1976). From 1973 through 1975, number of deer and elk pellet groups averaged 1.8 times greater on East Willow Creek than on the adjacent, unlogged, West Willow Creek where their numbers remained constant.

Although their production was not measured, mushrooms were abundant on unlogged sites after summer rains. Many of these mushrooms contribute substantially to late summer diets of mule deer (Hungerford 1970), and their presence is presumed to be at least a

partial cause for considerable use of mature stands during this season (Rasmussen 1941).

Relatively low understory production on the 2-year-old Hannagan Creek thinning is not unusual for recently logged sites, and is often related to degree of site disturbance and method of slash disposal (Reynolds 1962, Regelin and Wallmo 1978). Total production of deer and elk forage was significantly greater on East Willow Creek at 4 years than on Hannagan Creek at 2 years after logging, over most of the basal area range sampled. Seeding recently logged sites with preferred forage species would be one means of accelerating their value to deer and elk. It is not known when forage production will peak on these thinned sites, but herbage production on selectively logged ponderosa pine and mixed conifer sites on the North Kaibab Plateau increased annually from the second to the sixth year after logging, and then declined until, at age 11 to 15, it was comparable to uncut sites (Reynolds 1962). Consequently, the beneficial deer and elk forage response resulting from selective logging may be shorter-lived than that derived from clearcutting.

That significant differences were found between regression curves for unlogged and logged stands suggests the need for developing separate equations for pre- and post-logging conditions. In a comparison of thinned and unthinned ponderosa pine stands, Clary and Ffolliott (1966) found significantly greater understory production in thinned stands for basal area levels of less than 70 square feet per acre. They suggested that these differences could be caused by changes in forest overstory stocking arrangements and/or size class distribution. For example, extensive removal of smaller diameter trees (e.g., precommercial thinning or through natural thinning processes) from a multiple-age stand can result in a relatively high residual basal area and yet, substantial understory production resulting from better light conditions. Physical disturbances caused by logging (e.g., forest floor alterations, reduction in competing shrub or hardwood cover, or a reduction in overstory crown cover due to limb breakage) also may contribute to these differences.

Although clearcuts and the older thinned site produced more potential deer and elk forage than unthinned sites, maximum utilization of this additional forage can only be achieved through judicious integration of forest and wildlife management practices. Forest managers should consider how size, shape, and juxtaposition of cutting units will influence quality and availability of foraging areas, and hiding and thermal cover. Utilization of treated areas also will be influenced by availability of water, the manner in which logging slash is treated, and the location and design of roads as they influence disturbance from humans.

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Forest Vegetation of the White River National Forest in Western Colorado: A Habitat Type Classification

George R. Hoffman
Robert R. Alexander

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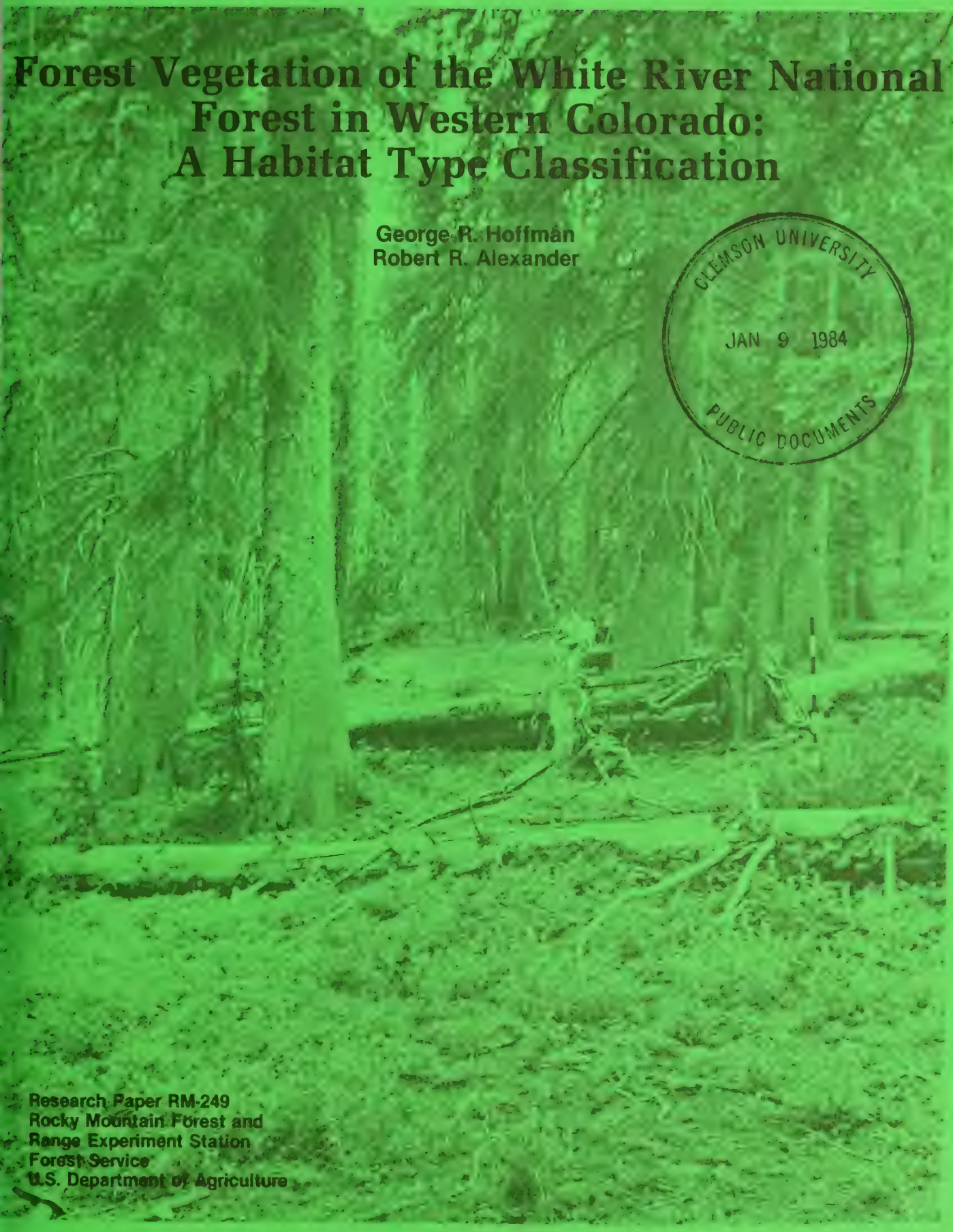

Research Paper RM-249
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

Abstract

A vegetation classification based on concepts and methods developed by Daubenmire was used to identify eleven forest habitat types in the White River National Forest. Included were five habitat types in the *Populus tremuloides* series, two in the *Abies lasiocarpa* series, and one each in the *Pseudotsuga menziesii*, *Pinus edulis*, *Picea pungens*, and *Quercus gambelii* series. A key to identify the habitat types and the management implications associated with each is provided.

Cover Photo.—Climax forest of the *Abies lasiocarpa/Vaccinium scoparium* habitat type on the Holy Cross District. This stand has a basal area of 357 square feet per acre (82 m^2/ha) and is more than 300 years old.

USDA Forest Service
Research Paper RM-249

August 1983

Forest Vegetation of the White River National Forest in Western Colorado: A Habitat Type Classification

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Forest Vegetation of the White River National Forest in Western Colorado: A Habitat Type Classification

George R. Hoffman and Robert R. Alexander

Forest vegetation on the White River National Forest nd adjacent areas has been studied previously to a mited extent, but this study comprehensively categorizes and describes forest habitat types based on uantitative data. Many earlier studies of forest vegetaion were management-oriented or autecologic in scope, ut a few are relevant to the present study. In a recently ompleted phyto-edaphic study, Hess and Wasser[2] described and classified grassland, shrubland, and forestand vegetation on the White River and Arapaho National Forests. Although the sampling methods and omenclature differ from the study reported here, it is vident that at least eight of the habitat types described n this paper were observed. Adjacent to the White iver to the north, Hoffman and Alexander (1980) described 11 habitat types on the Routt National Forest. even of these also occur on the White River. Further orth, on the Medicine Bow National Forest in southern Wyoming, Wirsing and Alexander (1975) described five abitat types. Three of these also occur on the White iver. On the Gunnison National Forest to the south, angenheim (1962) described several biotic communities n the Crested Butte area, which appear from general escriptions to be similar to two of the habitat types on he White River.

This cooperative study was started in 1979 to (1) identify and describe the forest habitat types in the White River National Forest on the basis of both reconnaissance and intensively sampled plots well distributed ver the whole Forest, (2) relate the habitat types to soils nd climatic data, (3) describe successional patterns of orest vegetation, and (4) relate White River forest habiat types to other Rocky Mountain forests with similar lassifications. The habitat type classification[3] completed in 1982 is based on concepts and methods developed by Daubenmire and Daubenmire (1968), Hoffman nd Alexander (1976), Hoffman and Alexander (1980), fister et al. (1977), and Steele et al. (1981).

The results reported here are intended for two primary audiences: forest managers and land use planers, who want a working tool to use on the White River National Forest, and ecologists, who want a research ool to use in related studies. Not all readers will find ach category of information of equal value.

[2]*Hess, Karl, and Clinton H. Wasser. Grassland, shrubland, and orestland vegetation associations on the White River-Arapaho National Forests, 335 p. Unpublished report on file at Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. (FS-RM-MFRWU-1252).*

[3]*Hoffman, George R. A classification of forest habitat types on he White River National Forest, 123 p. Unpublished report on file at Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. (FS-RM-MFRWU-1252).*

STUDY AREA

Physiography and Geology

The White River National Forest in western Colorado (fig. 1) lies within the Southern Rocky Mountain Province described by Fenneman (1931). The northern part of the Forest is located on the Colorado Plateau, a large, early erosional surface formed by uplift and subsequent peneplanation. It is bounded on the north by the Green River Basin, on the west by the Uinta Basin, and on the south and east by the Colorado River. The northern segment of the Plateau is a large area of late tertiary andesitic and basaltic remnants of volcanic activity which form the Flattops. From the Flattops to the Colorado River south and east, the central and southern segments of the Plateau are characterized by level to rolling topography severely dissected by streams and rivers that form deep canyons, some of which are 2,000 feet (610 m) below the top of the Plateau. In these segments, the Plateau is composed of Paleozoic sedimentary deposits of limestone, sandstone, and siltstone underlain by Precambrian granites and schists. The Park-Gore Ranges form the backbone of the northeastern White River National Forest. This area is bounded on the north by Middle Park, to the east by the Blue River, to the south by the Mosquito Range, and to the west by the Colorado River. Structurally these ranges resemble the Front Range to the east. Both the Park and Gore Ranges are faulted anticlines with Precambrian igneous cores. However, prominently edged and upturned sedimentary rock layers on the western flank of the Gore Range are in sharp contrast to the physiography of the eastern flank of the Park Range where fewer resistant sedimentary rock layers remain. The southern White River National Forest, south of the Colorado River and west of the Gore and Mosquito Ranges, is comprised of two major mountain systems. The Sawatch Range, a massive faulted anticline intruded by Precambrian igneous rocks, dominates the southeastern part of the Forest. On the northern end and along the western flank of the Sawatch Range, including Red Table Mountain, red shales, siltstones, limestones, sandstones, and conglomerates predominate at middle and lower elevations. The Elk and West Elk Mountains are westward continuations of the Sawatch Range and characterize the southwestern White River National Forest. However, these ranges are not faulted anticlines. They are composed of Paleozoic sedimentary layers thrusted westward over one another and highly metamorphosed. The Maroon Bells in the southern Elk Mountains are an example of highly metamorphosed sandstones and shales.

Figure 1.—The White River National Forest showing locations of study areas and current designated wilderness areas.

Climate

Precipitation in the White River National Forest increases with elevation. Mean annual precipitation varies from about 20 to 25 inches (51 to 64 cm) at 8,500 feet (2,590 m) in the *Populus tremuloides* forest zone to about 35 to 40 inches (89 to 102 cm) at 10,000 feet (3,050 m) in the *Abies lasiocarpa* forest zone. At these elevations, somewhat more than one-half of the total precipitation falls as snow during the six coldest months of the year.

Mean annual temperature in the *Populus tremuloides* forest zone is about 41° F (5° C), with a January mean of 23° F (−5° C) and a July mean of 61° F (16° C). In th *Abies lasiocarpa* forest zone, mean annual temperatur is about 34° F (1° C), with a January mean of 18°] (−8° C) and a July mean of 55° F (13° C).

The limited temperature and precipitation data fron published records are useful in characterizing th White River National Forest in broad, general terms However, in regions with massive mountain ranges deep valleys and canyons, and high plateaus, precipita tion and temperatures are so variable that it is difficul to provide any meaningful climatic information for given locality.

METHODS

Preliminary work began in 1979 with a reconnaissance survey of about 150 sites throughout the White River National Forest. At each site, plants present were listed, their abundance was noted, successional status of the stand and dominant tree species were estimated, possible habitat types were listed, and study sites noted, with a brief description of physiographic and edaphic factors.

During the summers of 1980 and 1981, 51 stands were intensively sampled. These stands were mostly old-growth and climax or in the late seral stages of succession. Old-growth stands were not available in every locality because of extensive past disturbance by fire, insects, logging, and grazing. Stands were representative of the forest communities characterized by the following tree species: *Populus tremuloides, Pseudotsuga menziesii, Pinus contorta, Abies lasiocarpa,* and *Picea engelmannii.*

In each stand, a 49.2- by 82.0-foot (15- by 25-m) plot was laid out with the long dimension parallel to contour. It was located in the most homogeneous part of the stand and away from ecotones and other disturbances. Each main plot was then subdivided into three 16.4- by 82.0-foot (5- by 25-m) subplots. Within each 4,036-square-foot (375-m²) main plot, all trees taller than 3.28 feet (1 m) were measured and recorded by 0.328-foot (1-dm) diameter classes. Trees less than 3.28 feet (1 m) tall were counted and recorded in two 3.28- by 82.0-foot (1- by 25-m) transects along the inner sides of the central subplot.

Canopy coverage of all understory shrubs, forbs, and graminoids was estimated in fifty 7.9- by 19.7-inch (2- by 5-dm) microplots placed systematically along the inner sides of the central subplot. Canopy coverage of each species was recorded as one of six coverage classes (1-5%, 6-25%, 26-50%, 51-75%, 76-95%, and 96-100%). Also listed were those species not occurring in the 50 microplots but present in the 4,036-square-foot (375-m²) main plot.

Finally, 25 cores representing the upper decimeter of the mineral soil were collected from each stand. These samples were air dried in the field, then were composited for laboratory analysis.

ANALYSIS OF DATA

Tree-size class data were combined according to habitat type, and mean values for each size class in each habitat type are recorded (table A-1).

For each microplot examined, the midpoints of the coverage classes were used to calculate average percent coverage for each shrub, graminoid, and forb species. Frequency, the percentage of microplots in which a species occurs in each stand, was also determined for each species. Coverage and frequency data for all understory species plus site data are shown in appendix tables A-2 through A-6. Species coverage and selected stand characteristics were then transferred to an association table. Stands were arranged and rearranged to group stands with similar floristic composition and climax tree species. Habitat type separation was based on a consideration of both overstory and major shrubs, graminoids, and forbs (Daubenmire 1952, Daubenmire and Daubenmire 1968, Mueller-Dombois and Ellenberg 1974).

Soil texture was determined by a modified Bouyoucos method (Moodie and Koehler 1975). Other soil characteristics determined were pH (using a glass electrode on the saturated soil paste), cation exchange capacity, and exchangeable Ca, Mg, and K on the ammonium acetate extract. N by the Kjeldahl method, OM by a modified Walkley-Black method, and P by the Bray technique were also determined for each sample (Moodie and Koehler 1975).

Nomenclature for plants collected in this study follows Harrington (1954) and Weber (1976). Although plants were collected at various times during the growing season, some taxonomic difficulties persisted. Most of these resulted from hybridization among two or more species which have not been studied systematically to clarify the taxonomy. Other taxonomic difficulties related to lack of flowering specimens. Where considerable variation made it impossible to determine species, genera only were used.

ECOLOGIC TERMS AND CONCEPTS

Because terminology in ecology is not uniformly used or understood, the terms and concepts used in this paper are defined. Unless stated otherwise, all terms follow usage proposed by Daubenmire and Daubenmire (1968).

"Climax vegetation" is that which has attained a steady state with its environment; without disturbance, species of climax vegetation successfully maintain their population sizes. The following classification of climax vegetation was first proposed by Tansley (1935). Daubenmire (1968) further elaborated on the definition, usage, and limitations. Primary climaxes develop on habitats where recurring disturbance is not a factor influencing the structure or composition of the vegetation. "Climatic climax" vegetation develops on normal topography with fairly deep, well-drained, loamy soil. Normal topography in mountainous regions is necessarily different from that of plains regions. The absence of recurrent disturbance is also critical in defining climatic climax vegetation. Where soils or topography exert sufficient influence to produce self-perpetuating vegetation distinct from the climatic climax, the terms "edaphic climax" and "topographic climax," respectively, are used to describe the steady-state vegetation. Where special topographic conditions also favor the development of edaphic conditions distinct from the normal, the term "topo-edaphic climax" is often used in descriptions of the resulting steady-state vegetation.

Where recurring disturbance, such as grazing or fire, exerts a predominant influence on the composition or structure of steady-state vegetation the term "dis-

climax" is used. Two common disclimaxes are the "zootic climax" and the "fire climax." In the absence of the disturbing factor, or factors, it is possible the vegetation will revert to the primary climax.

Habitat type is the basic unit in classifying lands or sites based on potential (climax) natural vegetation. A habitat type represents, collectively, all parts of the landscape that support, or have the potential of supporting the same climax vegetation. Series is the next higher category of classification (Hoffman and Alexander 1976); each habitat type is named for its (climax) plant association. For example, all habitat types with *Pseudotsuga menziesii* as the potential climax dominant are grouped into the *Pseudotsuga menziesii* series. The series is more than an artificial grouping of habitat types using the potential climax overstory dominant as the convenient thread of continuity. There is an ecologic basis for grouping habitat types into series. For example, *Pseudotsuga menziesii* occupies areas that are warmer and drier than areas where *Populus tremuloides* is climax. Continuing higher into the mountains, *Pinus contorta, Picea engelmannii,* and *Abies lasiocarpa* successively become the dominant species. In the absence of adequate climatic data for the White River National Forest, it is assumed that these self-perpetuating populations of dominant trees are related to the macroclimate, whereas the undergrowth vegetation is related more to microclimate and soils. Stands in a series have the same general appearance whether they are in the White River National Forest or in nearby forests of Colorado and Wyoming (Hoffman and Alexander 1980, Wirsing and Alexander 1975). Habitat types within a series are distinguished on the basis of undergrowth vegetation. For example, *Populus tremuloides* is widely distributed as a seral and climax species in western Colorado. Where it is climax, several undergrowth unions occur. The most luxuriant and widely distributed is the *Thalictrum fendleri* union. On some sites, a union formed by the single species *Heracleum sphondylium* forms a conspicuous layer. Where *Heracleum sphondylium* dominates the undergrowth, it forms another habitat type. Thus *Populus tremuloides/Thalictrum fendleri* and *Populus tremuloides/Heracleum sphondylium* are two distinct habitat types even though the *Thalictrum fendleri* union may be well-represented in both.

The White River National Forest has been disturbed by fire, logging, and grazing for many years. Because of these disturbances, not all of the land area currently supports climax vegetation. It is possible that much of the area of a habitat type will never attain climax status. Nevertheless, it is important to consider land units in terms of their potential status. The practical value of habitat type classifications is only beginning to be realized in areas of tree productivity, disease and insect susceptibility, potential for producing browse, soil moisture depth, and tree regeneration (Arno and Pfister 1977; Daubenmire 1961, 1973; Layser 1974; Pfister 1972). The habitat type concept offers a useful approach to managing forest resources.

HABITAT TYPES

Forest vegetation in the White River National Forest ranges from the xerophytic *Pinus edulis-Juniperus* sp.-dominated vegetation at the warmer, drier low elevations to the mesophytic *Abies lasiocarpa-Picea engelmannii*-dominated vegetation at the cooler, moister high elevations. Because of time limitations, and the fact that most of the lower elevation forests were outside the White River boundaries and had been heavily grazed, the *Pinus edulis-Juniperus* spp.- and *Quercus gambelii*-dominated vegetation was not extensively sampled. However, reconnaissance surveys were made on the areas dominated by these vegetation types.

Pseudotsuga menziesii Series

Pseudotsuga menziesii is not widespread or abundant on the White River National Forest. It grows only in small stands on steep slopes with shallow soils (fig. 2).

The *Pseudotsuga menziesii* series was sampled in only two plots and one habitat type that were on west- to northwest-facing slopes, at elevations of 8,400 to 8,850 feet (2,560 to 2,700 m). *Pseudotsuga menziesii* is climax in some areas and seral to *Abies lasiocarpa* and/or *Picea engelmannii* in others. Dominant *Pseudotsuga menziesii* in these stands range from about 80 to 120 years old at breast height. Basal areas on the study plots ranged from 131 to 135 square feet per acre (30 to 31 m^2/ha). Tree sizes range from seedlings to the 12- to 16-inch (3- to 4-dm) d.b.h. class. Tree populations and undergrowth data for *Pseudotsuga menziesii* stands are shown in tables A-1 and A-2.

Pseudotsuga menziesii/Pachistima myrsinites

Description.—The *Pseudotsuga menziesii/Pachistima myrsinites* habitat type is recognized by the presence and reproductive success of *Pseudotsuga menziesii* (fig. 3) and by the abundance and dominance of *Pachistima myrsinites* in the undergrowth (fig. 4). Other important shrub species are *Berberis repens, Juniperus communis, Rosa* sp., and *Symphoricarpos oreophilus.* Herbaceous plants are not abundant in this habitat type. *Calamagrostis rubescens, Carex geyeri, Aquilegia caerulea, Arnica cordifolia, Galium boreale, Solidago* sp., and mosses and lichens are most common.

Hoffman and Alexander (1980) described this habitat type on the Routt National Forest in Colorado just north of the White River. No *Pseudotsuga*-dominated habitat types were reported in the Medicine Bow Mountains of southern Wyoming (Wirsing and Alexander 1975). In the Bighorn Mountains of north-central Wyoming, *Pseudotsuga* is widespread and dominates the *Pseudotsuga menziesii/Berberis repens* and *Pseudotsuga menziesii/Physocarpus monogynous* habitat types (Hoffman and Alexander 1976). *Pseudotsuga menziesii*-dominated habitat types are also common and widespread in north

Figure 2.—Typical occurrence of *Pseudotsuga menziesii* between Eagle and Gypsum, in an open stand, on a steep slope, with very shallow soil.

Figure 3.—*Pseudotsuga menziesii/Pachistima myrsinites* habitat type. In this stand, on a steep west-facing slope, the trees are relatively dense. The meter stick used for scale in this and subsequent photos is painted in 1-dm increments.

Figure 4.—The *Pachistima myrsinites* undergrowth union. The dominant species here is *Pachistima* with lesser abundance of *Berberis repens*. Lichen-encrusted rock outcroppings, left side of photo, are relatively common in this habitat type.

ern Utah (Mauk and Henderson[4]), Montana (Pfister et al. 1977), and northern and central Idaho (Daubenmire and Daubenmire 1968, Steele et al. 1981).

Management Implications.—Little information is available on the management of this limited habitat type. Timber productivity is below the average for *Pseudotsuga*, because it grows in relatively dry situations. Regeneration is likely to be difficult to obtain if stands are clearcut. Group selection and shelterwood cuttings approximate the regeneration patterns observed in natural forests. Livestock forage production is low, and the potential for increasing it is not very great. Big game heavily browse the shrub species at times. Shrub species can be increased by maintaining low overstory basal areas. The potential for increasing natural runoff is not very great because of the limited area occupied by the habitat type.

Populus tremuloides Series

Populus tremuloides is widely distributed in western Colorado. In the White River National Forest, it grows at elevations ranging from about 8,000 feet (2,440 m) to about 10,500 feet (3,200 m). At the elevational extremes, *Populus* is often stunted. At the highest elevations, it grows on very rocky soils with sparse undergrowth (fig. 5), while at the lower edge of its range *Populus tremuloides* often grows in thickets with *Quercus gambelii*, *Amelanchier alnifolia*, and *Prunus virginiana* (fig. 6). Throughout most of its range on the White River however, it forms large stands of sizable trees on all exposures, particularly at elevations ranging from 8,400 feet (2,530 m) to 10,000 feet (3,050 m) (table 1).

There has been considerable discussion regarding the role of *Populus tremuloides* as a climax and/or seral species in the Rockies; both assessments may be correct. In some areas, *Populus tremuloides* dominates sites where fires have destroyed coniferous forests. In time conifers gradually replace *Populus tremuloides* (fig. 7). Succession to coniferous forest apparently is slowed significantly by changes in soil resulting from site occupancy by the deciduous *Populus*. In other areas *Populus tremuloides* forests appear to be climax without evidence of conifer invasion. This is especially evident where large burns have eliminated the coniferous seed source from at least the central portion of the burned area, but it is also evident in some areas where a coniferous seed source is present. According to Mueggler (1976), complete conversion of *Populus* stands to coniferous climax forest may require more than 1,000 fire-free years. The origin of both seral and climax *Populus tremuloides*-dominated forests may be the same—destruction of coniferous forest by repeated fires.

[4]*Mauk, Donald L., and Jan A. Henderson. Forest habitat types of northern Utah, 303 p. Unpublished report, Department of Forestry and Recreation, Utah State University, Logan. On file at Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. (FS-RM-MFRWU-1252).*

Figure 5.—*Populus tremuloides* at 10,200 feet (3,100 m) is stunted and occurs on steep slopes with shallow soils.

Table 1.—Selected topographic and edaphic characteristics of the habitat types in the White River National Forest

Habitat type	Stands sampled	Elevation	Soil texture[1]	pH[1]	Organic matter
	number	*m*			*percent*
Populus tremuloides / Symphoricarpos oreophilus	8	2,652-2,858	Loam-clay loam	5.8-6.6	3.4-7.2
Populus tremuloides / Heracleum sphondylium	2	2,713-2,957	Clay loam	6.3-7.4	3.8-5.2
Populus tremuloides / Carex geyeri	4	2,972-3,033	Loam-sandy loam	6.0-6.2	2.0-3.1
Populus tremuloides / Thalictrum fendleri	12	2,560-3,048	Clay loam-sandy loam	5.8-6.7	3.2-6.6
Populus tremuloides / Pteridium aquilinum	1	2,682	Clay loam	6.0	5.2
Pseudotsuga menziesii / Pachistima myrsinites	2	2,560-2,697	Sandy loam	6.5	2.4
Abies lasiocarpa / Carex geyeri	5	2,713-2,960	Loam-clay loam	5.4-6.1	2.8-5.7
Abies lasiocarpa / Vaccinium scoparium	17	2,743-3,414	Silty loam-sandy loam	4.8-5.7	1.6-5.9

[1]*Upper 1 dm of soil.*

Many *Populus tremuloides* forests are even-aged; the trees originate from sprouts after a disturbance (fig. 8). Baker (1925) suggested that in stands where older trees die naturally over a short time span, an even-aged replacement stand may develop. Other stands are uneven-aged, and sprouts apparently provide enough young trees to perpetuate the species indefinitely (fig. 9). Two-storied stands are also relatively common and can develop when surface fires burn quickly through mature stands, thereby stimulating sprouting (fig. 10).

On the White River National Forest, those plant communities dominated by *Populus tremuloides* which show no indication of being replaced by coniferous species are considered to be habitat types dominated by *Populus tremuloides*.

This series is represented by 26 plots, located on all aspects, at elevations of 8,400 to 10,000 feet (2,530 to 3,050 m). Five habitat types were recognized. Dominant *Populus tremuloides* in these stands range from about 100 to 180 years old at breast height. Basal areas on the study plots range from 96 to 300 square feet per acre (22 to 69 m^2/ha). Tree sizes usually ranged from seedlings to the 16- to 20-inch (4- to 5-dm) d.b.h. class. Occasionally, there were scattered trees in the 20- to 24-inch (5- to 6-dm) d.b.h. class. Not all d.b.h. classes were represented on each plot. Tree population and undergrowth data for *Populus tremuloides* stands are shown in tables A-1, A-3, and A-4.

Figure 6.—At mid-elevation on this slope, *Populus* occurs on deeper, colluvial soils. At its lower edge, it adjoins the lower-statured *Quercus gambelii*. On the far right is *Prunus virginiana* and *Amelanchier alnifolia*.

Populus tremuloides/Symphoricarpos oreophilus

Description.—The *Populus tremuloides/Symphoricarpos oreophilus* habitat type, represented by eight stands, is recognized by the consistent presence and reproductive success of *Populus tremuloides*, and the abundance and dominance of *Symphoricarpos oreophilus* in the undergrowth (fig. 11). This habitat type occupies the lower edge of the *Populus* zone on the Forest and is the driest *Populus tremuloides* habitat type. In the direction of drier habitats, *Populus tremuloides* is replaced by *Quercus gambelii*, *Pinus edulis-Juniperus* spp., or *Artemesia tridentata*-dominated vegetation. If replaced by *Quercus gambelii*, it forms the *Quercus gambelii/Symphoricarpos oreophilus* habitat type.

In addition to *Symphoricarpos oreophilus*, important shrubs are *Amelanchier alnifolia*, *Berberis repens*, *Prunus virginiana*, *Rosa* sp., *Pachistima myrsinites*, *Sambucus racemosa*, and *Sorbus scopulina*. The most important species in the rich mixture of graminoids and forbs are *Elymus glaucus*, *Galium boreale*, *Geranium richardsonii*, *Lathyrus leucanthus*, *Taraxacum* sp., *Thalictrum fendleri*, and *Vicia americana*.

Hoffman and Alexander (1980) identified this habitat type on the Routt National Forest in northwestern Colorado. A similar vegetation association occurs further south, on the Gunnison National Forest (Langenheim 1962, Morgan 1969). In the Medicine Bow National Forest and in the Bighorn Mountains, there are no understory unions dominated by *Symphoricarpos* (Wirsing and Alexander 1975, Hoffman and Alexander 1976). In western Wyoming, northern Utah, and central and southeastern Idaho, Mauk and Henderson,[4] Mueggler and Campbell (1982), Steele et al. (1979), and Youngblood and Mueggler (1981) identified a *Populus tremuloides/Symphoricarpos oreophilus*-dominated vegetation with similar associated undergrowth. Mueggler and Campbell (1982) and Youngblood and Mueggler (1981) described this vegetation as a community type, but indicated that similar community types were probably stable and very likely valid habitat types.

Management Implications.—Timber productivity is low to moderate in this dry habitat type. Clearcutting and regenerating a new stand is usually the preferred way to handle these stands. Annual precipitation varies from 18 to 24 inches (46 to 61 cm) with about 9 to 12 inches (23 to 30 cm) of runoff. Potential for increasing streamflow under management is unknown. This habitat type is spring and fall big game range, and use may be heavy. In years of low snowfall, it may be used all winter. Browse production is moderate because of the presence of several tall shrubs that are highly palatable

Figure 7.—Where conifers succeed *Populus tremuloides*, *Abies lasiocarpa* is more agressive in becoming established.

Figure 8.—*Populus tremuloides* is present in four diameter classes in this stand, but the overstory is dominated by trees of 4-8 inches (1-2 dm) and 8-12 inches (2-3 dm) dbh sizes. In this *Populus tremuloides/Thalictrum fendleri* habitat type, basal area is 196 square feet per acre (45 m^2/ha).

for big game. The habitat type is summer range for livestock. Under proper grazing management, herbage production may be as high as 500 to 800 pounds per acre (560 to 900 kg/ha), with high protein browse important. This habitat type has fairly good scenic quality, but generally with less favorable color contrast than with mixed *Populus*-conifer stands. Mature and open stands generally are more visually attractive, with the shrub understory providing both texture diversity and variety in seasonal color.

Populus tremuloides/Thalictrum fendleri

Description.—This habitat type, represented by 12 stands, is the most widespread of the *Populus*-dominated habitat types in the White River National Forest (fig. 12). It is recognized by the consistent reproductive success of *Populus tremuloides* and the high coverage of *Thalictrum fendleri* in the undergrowth. In nine of the stands sampled, *Populus tremuloides* was the only tree species. In the other stands, there was a scattering of *Abies lasiocarpa* seedlings, but no clear evidence that these stands were moving toward a climax dominated by conifers. Most of the stands in this habitat type appear to develop into uneven- or broad-aged stands that are self-perpetuating.

Symphoricarpos oreophilus is the most common shrub in the undergrowth. Important graminoids are *Bromus ciliatus*, *Carex geyeri*, and *Elymus glaucus*. Common forbs include *Achillea millefolium*, *Aquilegia caerulea*, *Aster engelmannii*, *Delphinium barbeyi*, *Erigeron* sp.,

Figure 9.—In this stand, *Populus tremuloides* is present in seven diameter classes, ranging from 0-4 inches (0-1 dm) to 24-28 inches (6-7 dm). The trees are more evenly distributed among the size classes larger than 0-4 inches (0-1 dm) which has the largest number of stems. This stand is also in the *Populus tremuloides/Thalictrum fendleri* habitat type. Basal area is 300 square feet per acre (69 m^2/ha).

Figure 10.—The two-storied structure common in *Populus/Thalictrum* habitat types.

Figure 11.—The *Populus tremuloides/Symphoricarpos oreophilus* habitat type. Dominance of *Symphoricarpos* in the undergrowth is evident.

Figure 12.—The *Populus tremuloides/Thalictrum fendleri* habitat type is widespread on the White River National Forest. In this stand, five diameter classes are present, ranging from 0-4 inches (0-1 dm) to 16-20 inches (4-5 dm). The undergrowth is a luxuriant mixture of mostly herbaceous species characteristic of the *Thalictrum fendleri* union.

Fragaria sp., *Galium boreale*, *Geranium richardsonii*, *Heracleum sphondylium*, *Hydrophyllum capitatum*, *Lathyrus leucanthus*, *Ligusticum porteri*, *Osmorhiza* sp., *Thalictrum fendleri*, *Valeriana occidentalis*, and *Vicia americana* (fig. 13).

Hoffman and Alexander (1980) described this habitat type on the Routt National Forest, to the north of the White River. In the Crested Butte area of the Gunnison National Forest, Langenheim (1962) described *Populus*-dominated forests that appear to be similar to the *Populus tremuloides/Thalictrum fendleri* habitat type. Hess (1981) described a *Populus tremuloides/Thalictrum fendleri* habitat type on the Arapaho and Roosevelt National Forests, in north-central Colorado. In western Wyoming, and central and southeastern Idaho, Mueggler and Campbell (1982), and Youngblood and Mueggler (1981) described a *Populus tremuloides/Thalictrum fendleri* community type where the successional status of *Populus tremuloides* was in doubt. No plant associations with the *Thalictrum fendleri* union prevalent under *Populus* were found in the Medicine Bow National Forest or the Bighorn Mountains (Hoffman and Alexander 1976, Wirsing and Alexander 1975).

Management Implications.—The *Populus tremuloides/Thalictrum fendleri* habitat type is the most productive for timber in the *Populus* series. Site quality ranges from average to high. Clearcutting in patches or small blocks and regenerating new stands is the most effective way to handle these stands. This habitat type is the best summer range for big game and for sheep. Forage production under proper grazing management can be as high as 3,000 pounds per acre (3,360 kg/ha). It also provides habitat for numerous nongame animals, but the management implications for them are unknown. This habitat type has the most visually appealing foreground of all *Populus*-dominated habitat types because of the usually wide spacing with large tree diameters and the abundance of wildflowers in the undergrowth. Soils are well developed, and erosion is usually not a problem except on deteriorated ranges. In some situations, potential for soil mass movement appears to be high, especially if the overstory is removed in large clearcut blocks. Annual precipitation is 25 to 40 inches (64 to 102 cm), with about one-half becoming runoff. Potential for increasing streamflow under management is unknown.

Populus tremuloides/Carex geyeri

Description.—The *Populus tremuloides/Carex geyeri* habitat type has a restricted distribution on the White River (fig. 14). The four stands sampled were on south-facing slopes where nutrient and organic matter content of the soils were lower than found under the two previously described *Populus* habitat types. *Populus tremuloides* was the only tree species in three stands and the dominant self-reproducing tree in the other stand. The undergrowth is dominated by *Carex geyeri* and has fewer species than stands with the *Thalictrum fendleri* union. Important shrubs include *Amelanchier alnifolia*, *Berberis repens*, *Pachistima myrsinites*, *Rosa* sp., and *Symphoricarpos oreophilus*. Herbaceous understory

Figure 13.—The density and richness of the *Thalictrum fendleri* union, conspicuous in the vicinity of the meter stick are *Aster engelmannii*, *Thalictrum fendleri*, *Osmorhiza occidentalis*, *Geranium richardsoni*, *Elymus glaucus*, *Lupinus argenteus*, *Delphinium barberi*, and *Ligusticum porteri*.

Figure 14.—The *Populus tremuloides/Carex geyeri* habitat type on a south-facing slope. *Populus* occurs in four diameter classes, ranging from 0-4 inches (0-1 dm) to 12-16 inches (3-4 dm). The understory is not as rich or dense as in the other *Populus tremuloides* habitat types.

species most conspicuous are *Bromus ciliatus, Arnica cordifolia, Carex geyeri, Elymus glaucus, Epilobium angustifolium, Achillea millefolium, Fragaria* sp., *Lathyrus leucanthus,* and *Smilacina racemosa* (fig. 15).

This habitat was not identified in the Routt National Forest north of the White River (Hoffman and Alexander 1980), but was found in the Arapaho and Roosevelt National Forests, in north-central Colorado (Hess 1981), and in Medicine Bow National Forest, in southern Wyoming (Wirsing and Alexander 1975). There were no vegetation associations dominated by *Carex geyeri* in the Bighorn Mountains (Hoffman and Alexander 1976). In northern Utah, Mauk and Henderson[4] described a similar *Populus tremuloides/Carex geyeri*-dominated vegetation association as a community type.

Management Implications.—Timber productivity on this dry habitat is average to below average. Clearcutting and regenerating a new stand is usually the most effective way to perpetuate these stands. This habitat type is fair summer-fall range for big game and cattle. Forage production varies from 400 to 800 pounds per acre (450 to 900 kg/ha) depending upon range condition and management practices. Overgrazing may reduce Carex cover and expose soils that are difficult to revegetate. Annual precipitation varies from 20 to 30 inches (51 to 76 cm) with about 10 to 15 inches (25 to 38 m) of runoff. Potential for increasing streamflow is unknown. Erosion, sedimentation, and mass movement potentials are low. This habitat type has fair scenic quality, with less favorable color contrast than with mixed *Populus*-conifer stands. In open stands, the shrub understory provides both texture and variety in seasonal color. It also provides a pleasing ground color contrast in the fall when *Carex* remains green after other undergrowth vegetation has withered and died.

Populus tremuloides/Pteridium aquilinum

Description.—This habitat type was not widespread on the White River and is represented by only one stand in the study (fig. 16). *Pteridium aquilinum,* like *Populus tremuloides,* establishes rapidly after fire. Often it is replaced as succession advances other undergrowth unions, although it can perpetuate itself indefinitely. In this stand, *Pteridium aquilinum* appears quite stable. The stand sampled is on McClure Pass. *Populus tremuloides* was the only tree species in the stand. The undergrowth is dominated by *Pteridium aquilinum.* Other important understory species are *Elymus glaucus, Aster engelmannii, Fragaria* sp., *Lathyrus leucanthus, Thalictrum fendleri,* and *Vicia americana.*

It has been suggested that *Pteridium aquilinum* is an indicator of site deterioration resulting from overgrazing. The stand studied had not been grazed recently, and whether past grazing history significantly affected the composition of the undergrowth is not known.

The *Populus tremuloides/Pteridium aquilinum* habitat type was identified on the Routt National Forest, where it was confined to poorly drained areas north of

Figure 15.—Conspicuous species of the *Carex geyeri* undergrowth union include *Carex geyeri, Elymus glaucus, Castilleja sulphurea, Thalictrum fendleri, Lathyrus leucanthus, Arnica cordifolia,* and *Aster engelmannii.*

Figure 16.—*Populus tremuloides/Pteridium aquilinum* habitat type. In this stand, *Populus* is represented by four diameter classes ranging from 0-4 inches (0-1 dm) to 12-16 inches (3-4 dm). *Pteridium* provides nearly 80 % canopy coverage in the undergrowth. Under the *Pteridium* are members of the *Thalictrum fendleri* undergrowth union.

40°20′25″N latitude (Hoffman and Alexander 1980). *Pteridium aquilinum* was not reported as growing in *Populus*-dominated forests, on the Gunnison National Forest, to the south (Langenheim 1962, Morgan 1969), although it has been observed to be abundant in those forests. Northward in Wyoming, Utah, Montana, and Idaho, no *Populus/Pteridium* habitat types have been reported (Hoffman and Alexander 1976; Mueggler and Campbell 1982; Pfister et al. 1977; Steele et al. 1979, 1981; Wirsing and Alexander 1975; Youngblood and Mueggler 1981).

Management Implications.—This habitat type is restricted in area, and to poorly drained sites. The potential for timber and forage production and infiltration is less than in the *Populus tremuloides/Thalictrum fendleri* habitat type, and the potential for increased erosion, surface runoff, and soil mass movement is greater. The potential for soil damage from logging equipment is high when soils are wet. Species richness in the understory tends to be poor. This habitat type is most likely to occur in locations where cold air drainage and frost damage to *Populus* reproduction is likely in cleared openings.

Populus tremuloides/Heracleum sphondylium

Description.—The *Populus tremuloides/Heracleum sphondylium* habitat type, represented by only two stands on southeast slopes, has limited distribution on the White River National Forest (fig. 17). *Populus tremuloides* is the only tree species present. Not all diameter classes are represented; neither stand contains trees in the 1-2 dm d.b.h. class. The understory is dominated by a tall layer (1-2 m) of *Heracleum sphondylium*. Under *Heracleum* are species of the *Thalictrum fendleri* union that includes *Bromus ciliatus, Elymus glaucus, Aquilegia coerulea, Geranium richardsonii, Senecio serra,* and *Thalictrum fendleri.*

Hoffman and Alexander (1980) described this habitat type on the Routt National Forest, in northwestern Colorado. On the Gunnison National Forest, south of the White River National Forest, Langenheim (1962) and Morgan (1969) reported *Heracleum* under more than half the mature *Populus* stands they examined. In western Wyoming, Youngblood and Mueggler (1981) described a *Heracleum lanatum* community type with similar undergrowth (*Heracleum lanatum* has been changed to *Heracleum sphondylium*). They suggested that this vegetation association occurred throughout Wyoming, but it was not found in the Bighorn Mountains or in the Medicine Bow National Forest (Hoffman and Alexander 1976, Wirsing and Alexander 1975). No *Populus/Heracleum*-dominated vegetation has been reported in Idaho or Montana (Mueggler and Campbell 1982; Pfister et al. 1977; Steele et al. 1979, 1981).

Management Implications.—Because this habitat type is quite similar in management implications to the *Populus tremuloides/Thalictrum fendleri* habitat type on the White River National Forest, the two can be treated in the same manner.

Figure 17.—The *Populus tremuloides/Heracleum sphondylium* habitat type. *Populus* is represented by trees ranging from 0-4 inches (0-1 dm) to 12-16 inches (3-4 dm) dbh. Undergrowth is dominated by *Heracleum sphondylium* which is flowering in this stand. Its coverage is 67%. Under the *Heracleum* are members of the *Thalictrum fendleri* undergrowth union.

Abies lasiocarpa Series

This series, represented by 22 plots, occupies the highest and coldest coniferous forest zone on the White River National Forest (table 1). These forests—dominated by *Abies lasiocarpa* and *Picea engelmannii*—are usually referred to as the subalpine forest zone on the White River National Forest. As throughout much of the Rocky Mountains, the subalpine forest zone is widespread and supports forests of considerable importance. On the White River National Forest, these forests are found on all aspects at elevations ranging from 8,900 feet (2,710 m) to 11,200 feet (3,410 m), a span of 2,300 feet (755 m). This zone generally has been considered to be about 2,000 feet (7,610 m) in elevational extent (Daubenmire 1943). It has been reported as low as 8,000 feet (2,625 m) to as high as 11,500 feet (3,500 m) in the central Rocky Mountains. In the White River National Forest, the lower elevational limits of *Abies lasiocarpa*-dominated forests and the upper elevational limits of the *Populus*-dominated forests overlap, although aspect and soils play some part in the forest distribution.

The habitat types described in this series are all named for *Abies lasiocarpa* as the climax dominant to be consistent with usage elsewhere (Daubenmire and Daubenmire 1968, Hoffman and Alexander 1976, 1980; Pfister et al. 1977; Steele et al. 1979, 1981; Wirsing and Alexander 1975). On the White River National Forest, *Picea engelmannii* is a co-climax dominant with little evidence that it will ever be completely replaced by *Abies lasiocarpa*. Young *Abies lasiocarpa* usually outnumber the young *Picea engelmannii*, because *Abies lasiocarpa* is more tolerant and reproduces by layering and from seeds, whereas *Picea engelmannii* reproduces almost entirely from seed. Because *Picea engelmannii* live longer, they are nearly always the largest trees in the stand. The only exception occurs in stands where *Picea engelmannii* has been severely attacked by the spruce beetle (*Dendroctonus rufipennis* Kirby). In most stands, *Pinus contorta* and/or *Populus tremuloides* are present as seral species. After disturbance, *Populus tremuloides* may establish initially to be succeeded by *Pinus contorta* which, in turn, is replaced by *Abies lasiocarpa* and *Picea engelmannii*. *Abies lasiocarpa* and *Picea engelmannii* can reestablish immediately with or without *Pinus contorta* and/or *Populus tremuloides*, depending on the topographic situation, the type of disturbance, and the availability of coniferous tree seed or the sprouting capacity of *Populus*.

Two habitat types were recognized in this series. Stands sampled ranged from 80 to more than 300 years old at breast height. Basal areas ranged from 28 to 409 square feet per acre (28 to 94 m^2/ha). Tree sizes ranged from seedlings to the 24- to 28-inch (6- to 7-dm) d.b.h. classes, with an occasional tree in the more than 30-inch class (8+ dm). Tree population and undergrowth data are shown in tables A-1, A-5, and A-6.

Abies lasiocarpa/Vaccinium scoparium

Description.—The *Abies lasiocarpa/Vaccinium scoparium* habitat type is represented by 17 plots. In the stands sampled, nine were climax or near climax, and eight were late seral succession. The habitat type is recognized by the almost constant presence and reproductive success of *Abies lasiocarpa* and by the abundance and understory dominance of *Vaccinium scoparium* in association with *Vaccinium myrtillus*. *Picea engelmannii* is present as a self-reproducing co-climax species (fig. 18).

The overstory of most of the stands is dominated by *Abies lasiocarpa* and *Picea engelmannii*. *Pinus contorta* is an important seral species, and still dominates some of the stands in late seral succession (fig. 19). However, the self-reproducing species in these stands are *Abies lasiocarpa* and *Picea engelmannii*, and no evidence was found to suggest a habitat type dominated by *Pinus contorta* in the White River National Forest. *Populus tremuloides* is only an occasional minor seral species. Ground cover varies from sparse to luxuriant. In general, undergrowth species richness declines from seral to climax successional stages and from young to old stands. In addition to *Vaccinium scoparium* and *Vaccinium myrtillus* which constitute more than 50% of the coverage, other important undergrowth species are *Arnica cordifolia*, *Carex geyeri*, *Pachistima myrsinites*, *Pedicularis racemosa*, and *Ramischia secunda* (fig. 20).

The *Abies lasiocarpa/Vaccinium scoparium* habitat type, or others very similar to it, occur throughout the Rocky Mountains (Hoffman and Alexander 1976, 1980; Mauk and Henderson[4]; Moir and Ludwig 1979; Pfister et al. 1977; Steele et al. 1979, 1981; Wirsing and Alexander 1975). However, there is considerable variability in the coverage of *Vaccinium scoparium* within this habitat type. Additionally, more broad-leaved herbaceous dicots occur in this habitat type on the western slope of the Rockies than on the eastern slope.

Management Implications.—Timber productivity varies considerably (Alexander 1967). Understory vegetation changes slowly after major disturbance, and competition is not severe between tree seedlings and understory vegetation, except where coverage of herbaceous dicots is high. There may be a manageable stand of advanced reproduction in much of this habitat type. While most silvicultural systems can be used (Alexander 1974), complete removal of the mature overstory by clearcutting in mixed stands where *Pinus contorta* makes up part of the overstory may result in an even-aged replacement stand of seral *Pinus contorta*. This also can happen with the final harvest cut under shelterwood methods, unless extreme care is taken in logging to protect advanced regeneration of *Abies lasiocarpa* and *Picea engelmannii*. In these mixed stands, using a standard or modified shelterwood system, the proportion of *Pinus contorta* retained in the first cut can be used to manipulate the amount of *Abies lasiocarpa* and *Picea engelmannii* in the stand. Clearcutting is likely to eliminate the chance for regeneration of *Picea engelmannii* on southerly exposures, for extremely long periods of time. Where protection from direct solar radiation and excessive soil moisture losses is necessary for survival of *Picea engelmannii* seedlings, standard or modified shelterwood are appropriate even-aged cutting methods. *Pinus contorta* may have to be planted to maintain forest cover, if clearings occur or are desired.

Figure 18.—The *Abies lasiocarpa/Vaccinium scoparium* habitat type on the Holy Cross District. This climax stand has a basal area of 410 square feet per acre (94 m^2/ha) and is over 300 years old. *Abies* and *Picea engelmannii* are the only tree species represented. *Vaccinium scoparium* provides 60% coverage in the undergrowth.

Figure 19.—The *Abies lasiocarpa/Vaccinium scoparium* habitat type. This stand is still dominated by *Pinus contorta*, but it is seral to *Abies* and *Picea engelmannii*.

Figure 20.—*Vaccinium scoparium* undergrowth union may also have *Vaccinium myrtellus* and *Arnica cordifolia*. Note the rather sparse character of the undergrowth and the cones of *Pinus contorta*.

Uneven-aged management with group selection and/or individual tree selection cutting can be used in irregular-structured stands, or where the combination of openings and high forest is required to enhance recreational opportunities and amenity values. Group selection is likely to perpetuate the existing species mix, but may increase the proportion of *Pinus contorta*. Individual tree selection will favor *Abies lasiocarpa* over *Picea engelmannii*, and in mixed stands the proportion of both *Abies lasiocarpa* and *Picea engelmannii* will be increased, especially if the initial cutting removes a large proportion of *Pinus contorta*.

The *Abies lasiocarpa/Vaccinium scoparium* habitat type is not heavily used by livestock, but is big game summer range. It occupies areas with the greatest potential for water yield (up to 20 inches (50 cm) of natural runoff annually) in the White River National Forest. Small patch (3- to 5-acre (1.24- to 2.02-ha)) or strip (400-foot (122-m)) clearcuts result in greater forage production for big game and larger increases in water available for streamflow than either shelterwood, group selection, or individual-tree selection cutting (Alexander 1977, Alexander and Edminster 1980, Leaf 1975, Leaf and Alexander 1975, Regelin and Wallmo 1978, Wallmo et al. 1972). Because forage production begins to decline in about 15 to 20 years, and water production in 20 to 30 years, new openings must be cut periodically to maintain these increases.

Abies lasiocarpa/Carex geyeri

Description.—This habitat type, represented by five stands generally on northwest to west aspects, is distinguished by the dominance of *Carex geyeri* in the undergrowth, and the scarcity of *Vaccinium scoparium*, and the near absence of *Vaccinium myrtillus* (fig. 21). The overstory dominants are *Abies lasiocarpa* and *Picea engelmannii*. *Pinus contorta* and *Populus tremuloides* are seral species, with *Populus tremuloides* a much more important seral species than in the *Abies lasiocarpa/Vaccinium scoparium* habitat type; however, neither seral species shows any significant evidence of self-perpetuation. Important undergrowth species in addition to *Carex geyeri* are *Arnica cordifolia, Aster engelmannii, Geranium richardsonii, Lathyrus leucanthus, Ligusticum porteri, Osmorhiza* sp., and *Thalictrum fendleri*.

This habitat type generally occurs at lower elevations and in drier situations than the *Abies lasiocarpa/Vaccinium scoparium* habitat type. At higher elevations, the *Abies lasiocarpa/Carex geyeri* habitat type is usually found on south and west aspects; whereas the *Abies lasiocarpa/Vaccinium scoparium* habitat type occurs on north and east aspects at upper elevations.

This habitat type was described in the Routt National Forest, in northwestern Colorado, by Hoffman and Alexander (1980). An *Abies lasiocarpa/Carex geyeri* habitat

type also has been reported in the Arapaho and Roosevelt National Forests in north-central Colorado (Hess 1981); the Medicine Bow Mountains in southern Wyoming (Wirsing and Alexander 1975); and in western Wyoming in Yellowstone National Park and the Teton National Forest (Steele et al. 1979). In Montana, an *Abies lasiocarpa/Carex geyeri* habitat type is a minor habitat type, occurring on cold, dry sites (Pfister et al. 1977), but is common in central Idaho on granitic soils (Steele et al. 1981). The habitat type does not occur in the Bighorn or Wind River Mountains of Wyoming (Hoffman and Alexander 1976, Steele et al. 1979) or in eastern Washington or northern Idaho (Daubenmire and Daubenmire 1968).

Management Implications.—Understory vegetation in this habitat type recovers slowly from major disturbance. Tree reproduction in this dry, cold habitat type is more difficult to obtain, and competition between tree seedlings and understory vegetation is more severe than in the *Abies lasiocarpa/Vaccinium scoparium* habitat type. In fact, if tree seedlings are slow to establish after clearcutting, the site may become fully occupied by *Carex geyeri*. *Pinus contorta* is the tree species most likely to compete successfully with *Carex geyeri* following major disturbance. Timber productivity is average to below average. Cutting methods applicable are similar to those suggested for the *Abies lasiocarpa/Vaccinium scoparium* habitat type; however, seral stands of *Pinus contorta* are more likely to be susceptible to mountain pine beetle than *Abies lasiocarpa/Carex geyeri* habitat types. Where there is an appreciable amount of either *Pinus contorta* or *Populus tremuloides* in the stands, clearcutting or simulated shelterwood is likely to increase their representation in the new stand. This habitat type provides forage for livestock and big game. Heavy grazing may reduce the *Carex geyeri* cover and expose soils difficult to revegetate. Natural runoff (15 inches (38 cm)) is less than in the *Abies lasiocarpa/Vaccinium scoparium* habitat type, but can be increased significantly using the same cutting methods suggested for *Abies lasiocarpa/Vaccinium scoparium* habitat type.

OTHER VEGETATION

There are other forest habitat types and associated vegetation on the White River National Forest. Those described below were not sampled quantitatively because of time limitations, but a number of stands in each were visited and quantitatively evaluated with notes on both overstory and undergrowth vegetation.

Quercus gambelii/Symphoricarpos oreophilus

Description.—The *Quercus gambelii/Symphoricarpos oreophilus* habitat type usually occupies a zone between the *Pinus edulis*-dominated vegetation below and the *Populus tremuloides*-dominated vegetation above. The *Quercus* zone may also contact the *Artemisia tridentata*-dominated vegetation at either its upper or lower margins (fig. 22); and in some places, it may occur above

Figure 21.—*Abies lasiocarpa/Carex geyeri* habitat type. This climax forest has a basal area of 322 square feet per acre (74 m²/ha). The generally untidy appearance is typical of climax forests of the *Abies lasiocarpa* series.

Figure 22.—The *Quercus gambelii/Symphoricarpos oreophilus* habitat type. The dense growth of *Quercus* is characteristic and produces thickets that are in some cases difficult to penetrate. This stand abuts the *Artemisia tridentata*-dominated shrub-steppe.

the *Populus*-dominated vegetation. Regardless of where it occurs relative to other vegetation, the *Quercus gambelii/Symphoricarpos oreophilus* habitat type is wetter than *Pinus edulis*- and *Artemisia*-dominated vegetation and drier than *Populus*-dominated vegetation.

The understory of this habitat type characteristically has both woody and herbaceous species, but is dominated by *Symphoricarpos oreophilus*. *Amelanchier alnifolia* and *Prunus virginiana* are important shrubs. *Wyethia amplexicaulis*, *Balsamorhiza sagittata*, and *Artemisia tridentata* are conspicuous in open areas, with *Wyethia* more important where grazing is heavy. This habitat type is well-developed in the southwestern part of the White River National Forest and occurs on the Routt National Forest (Hoffman and Alexander 1980). Southwest from the White River National Forest into the Gunnison and Grand Mesa National Forests, *Quercus*-dominated vegetation becomes more important. Wirsing and Alexander (1975) did not identify a *Quercus gambelii* habitat type on the Medicine Bow National Forest, in southern Wyoming, but did recognize a dry *Quercus gambelii* community in the foothills and lower canyons.

Management Implications.—Little is known about this dry habitat type. It has little value for timber other than for fuelwood or water production. *Quercus gambelii* regenerates vigorously from sprouts after clearcutting or fire. Value for livestock varies with the amount of graminoids in the understory. It provides spring and fall habitat for big game and food and cover for nongame animals.

Pinus edulis/Juniperus spp.

Description.—*Pinus edulis*, along with *Juniperus osteosperma*, *Juniperus scopulorum*, and *Juniperus monosperma*, dominate this habitat type at low elevations (6,100 feet (1,860 m) to 6,600 feet (2,010 m)) on the White River National Forest (fig. 23). Within this zone, *Juniperus* species are usually more prevalent on lower slopes, while *Pinus edulis* is more numerous on upper slopes. All stands examined in this habitat type grew on shallow, rocky soils. Dominance is often shared by *Pinus edulis* and the three *Juniperus* species. Both *Pinus* and *Juniperus* are represented by several size classes up to and including 12 to 16 inches (3 to 4 dm) d.b.h., with a few individuals as large as 16 to 20 inches (4 to 5 dm) d.b.h. Basal areas in four stands ranged from 74 to 235 square feet per acre (17 to 54 m²/ha).

The undergrowth in these stands is both woody and herbaceous, and in some areas is extremely sparse because of heavy grazing. The more conspicuous shrubs are *Artemisia tridentata*, *Atriplex canescens*, *Cercocarpus montanus*, *Chrysothamnus nauseosus*, *Philadelphus microphyllus*, and *Rhus aromatica*. Important graminoids are *Agropyron smithii*, *Bromus tectorum*, *Bouteloua gracilis*, *Festuca idahoensis*, and *Stipa comata*. The most common forbs are *Astragalus* sp., *Cryptantha* sp., *Eriogonum umbellatum*, *Haplopappus* sp., *Oryzopsis* sp., *Senecio integerrimus*, and *Sphaeralcea coccinea*. The *Pinus edulis/Juniperus* spp., habitat type is a minor component of the vegetation in the White River National Forest. It is best represented along the lower western

edge of the White River Plateau, but most stands are below the forest boundary. No *Pinus edulis/Juniperus* spp.-dominated vegetation grows within the boundaries of the Routt National Forest (Hoffman and Alexander 1980), but west and south of the White River National Forest, it becomes a conspicuous feature of the landscape.

Management Implications.—Little is known about this dry habitat type. It has little value for water or timber production, although both *Pinus* and *Juniperus* are cut for fuelwood and fenceposts. Historical records indicate that both *Pinus* and *Juniperus* have increased with protection from fire. Value for livestock varies with the amount of graminoids in the undergrowth. It is important winter range for deer and provides both food and cover for nongame species.

Picea pungens/Poa spp.

Description.—The *Picea pungens/Poa* spp. habitat type occurs along streams over much of the southern half of the White River National Forest. It is generally confined to narrow, streamside terraces and extends upslope for short distances in narrow canyons. Occasionally, a small grove of *Picea pungens* is found at higher elevations. Most stands have been disturbed; and in many places only a few scattered *Picea pungens* are left, surrounded by a rank growth of heliophytic shrubs and herbaceous vegetation. Both *Pseudotsuga menziesii* and *Populus tremuloides* grow in some stands with *Picea pungens*. In narrow, steep-walled canyons, *Abies lasiocarpa-Picea engelmannii*-dominated vegetation may mingle with *Picea pungens*-dominated vegetation (fig. 24).

Poa spp. are common in the undergrowth of most *Picea pungens* stands. Some of the other conspicuous undergrowth species include: *Amelanchier alnifolia, Berberis repens, Pachistima myrsinites, Rosa* sp., *Rubus parviflorus, Symphoricarpos oreophilus, Bromus ciliatus, Carex* spp., *Achillea millefolium, Fragaria* sp., *Galium boreale, Geranium richardsonii, Lathyrus leucanthus, Osmorhiza* sp., *Senecio wootonii*, and *Vicia americana*. Hess (1981) identified a *Picea pungens/Arnica cordifolia* habitat type in the Arapaho and Roosevelt National Forests, in north-central Colorado, but no other *Picea pungens*-dominated habitat types have been recognized in the central Rocky Mountains (Hoffman and Alexander 1976, 1980; Wirsing and Alexander 1975). A number of *Picea pungens*-dominated habitat types occur in the Southwest and in Utah (Mauk and Henderson,[4] Moir and Ludwig 1979).

Management implications.—This habitat type is primarily valuable for scenic beauty and for protection of streambanks. It is moderately productive for timber and often critically important for wildlife associated with riparian vegetation.

Figure 23.—The *Pinus edulis/Juniperus* spp. habitat type occurs on xeric habitats at low elevations. The undergrowth is relatively sparse and the soils are very shallow.

Figure 24.—*Picea pungens* occurs along streams and abuts *Abies lasiocarpa* and *Picea engelmannii* upslope. Fringing *Picea pungens* on the streamside is a band of deciduous shrubs. Stand is east of Basalt along the Frying Pan River.

Pinus ponderosa

Description.—As in the Routt National Forest (Hoffman and Alexander 1980), *Pinus ponderosa* is a very minor species in the White River National Forest. An occasional old specimen grows in stands of the *Pseudotsuga menziesii/Pachistima myrsinites* habitat type (fig. 25). Others grow on disturbed sites on steep rocky slopes, but there are no contiguous stands of *Pinus ponderosa* left on the White River National Forest. The few original stands were destroyed by logging and fire before 1900 (Sudworth 1898).

KEY TO THE FOREST HABITAT TYPES OF THE WHITE RIVER NATIONAL FOREST

1. Deciduous trees dominant and reproducing; conifers may be present but are ordinarily rare and are not reproducing sufficiently to become dominant
    2. *Quercus gambelii* dominant; other tree species absent or not dominant .. *QUERCUS GAMBELII/SYMPHORICARPOS OREOPHILUS* H.T.
    2. *Quercus gambelii* absent or not dominant; *Populus tremuloides* dominant
        3. Undergrowth dominated by *Symphoricarpos oreophilus* ..... *POPULUS TREMULOIDES/SYMPHORICARPOS OREOPHILUS* H.T.
        3. Undergrowth dominated by rich mixture of herbaceous plants; *Symphoricarpos oreophilus* may be present but is not dominant
            4. Undergrowth dominated by *Pteridium aquilinum* ..... *POPULUS TREMULOIDES/PTERIDIUM AQUILINUM* H.T.
            4. *Pteridium aquilinum* may be present in the undergrowth but is not dominant
                5. Undergrowth dominated by *Heracleum sphondylium* ..... *POPULUS TREMULOIDES/HERACLEUM SPHONDYLIUM* H.T.
                5. *Heracleum sphondylium* may be present in the undergrowth but is not dominant
                    6. Undergrowth dominated by *Carex geyeri*; *Arnica cordifolia* may also be important. Undergrowth may be a rich mixture of species, but *Thalictrum fendleri*, *Aster engelmannii*, *Geranium richardsonii*, and *Ligusticum porteri* are usually absent or not abundant ..... *POPULUS TREMULOIDES/CAREX GEYERI* H.T.
                    6. *Carex geyeri* present in the undergrowth ordinarily; but the rich undergrowth is dominated by *Thalictrum fendleri* with considerable coverage provided by *Aster engelmannii*, *Geranium richardsonii*, and *Ligusticum porteri* ..... *POPULUS TREMULOIDES/THALICTRUM FENDLERI* H.T.

1. Deciduous trees may be present but are neither dominant nor reproducing sufficiently to maintain their populations; conifers or junipers dominant and reproducing satisfactorily
    7. *Pinus edulis* and/or *Juniperus scopulorum*, *Juniperus osteosperma*, or *Juniperus monosperma* dominant and reproducing. Other gymnosperms absent ... *PINUS EDULIS/JUNIPERUS* SPP. H.T.
    7. *Pinus edulis*, *Juniperus scopulorum*, *Juniperus osteosperma*, and *Juniperus monosperma* absent or rare
        8. *Pseudotsuga menziesii* dominant and reproducing; other conifers may be present but are occasional or rare and are not reproducing in sufficient numbers to maintain a population .. *PSEUDOTSUGA MENZIESII/PACHISTIMA MYRSINITES* H.T.

8. *Pseudotsuga menziesii* absent or rare or occasional and not reproducing
    9. *Picea pungens* dominant and reproducing. Other tree species may be present but are occasional or rare and are not reproducing in sufficient numbers to maintain a population . . *PICEA PUNGENS/POA* SPP. H.T.
    9. *Picea pungens* absent or very rare and not reproducing. *Abies lasiocarpa* and/or *Picea engelmannii* dominant and reproducing. *Pinus contorta* may be an important member of the overstory
        10. Undergrowth dominated by *Vaccinium scoparium* . *ABIES LASIOCARPA/ VACCINIUM SCOPARIUM* H.T.
        10. *Vaccinium scoparium* may be present but is not dominant. The undergrowth dominated by *Carex geyeri* . . . . *ABIES LASIOCARPA/CAREX GEYERI* H.T.

The distribution and successional status of tree species in relation to habitat type are shown in figure 26.

DISCUSSION

Validity of Habitat Type Classification

The practical value of the habitat type classifications has only begun to be realized in areas of vegetation mapping, relation to tree growth, susceptibility to diseases, production of browse species for game animals, and in providing a framework within which to relate additional basic or applied biological studies (Daubenmire 1961, 1973, 1976).

The classification system, while using vegetation as the indicator of site potentials, combines available related information on soil and climate. While initially using vegetation as the criterion of delimiting habitat types, this approach also takes a holistic view of units of land area. The older the stands observed, the more closely they approximate the potential (climax or near climax) of the landscape units studied (Daubenmire 1976).

This classification system utilizes both overstory and undergrowth vegetation in recognizing habitat types. In this study, the two major vegetation zones are dominated by *Populus tremuloides*, and *Abies lasiocarpa* and *Picea engelmannii*. It is apparent that the *Populus* zone on the White River National Forest and elsewhere in Colorado is warmer and drier than the *Abies* zone. Edaphic factors are also more alike within than between zones.

The classification of habitat types recognizes climax tree species in an area; these are given primary consideration, and important seral species are noted. Undergrowth vegetation is then used to indicate habitat types within the zone where a given tree species is climax. Within the *Populus* zone of the White River National Forest, five habitat types were recognized based on relatively few species. The *Populus tremuloides/*

Figure 25.—On exposed xeric sites, an occasional *Pinus ponderosa* occurs, often in association with *Pseudotsuga menziesii*. This stand is on a south-facing slope above the Frying Pan River east of Basalt.

Habitat Type / Species	*Pinus edulis*	*Juniperus scopulorum, J. osteosperma, J. monosperma*	*Quercus gambelii*	*Pinus ponderosa*	*Pseudotsuga menziesii*	*Populus tremuloides*	*Pinus contorta*	*Abies lasiocarpa*	*Picea engelmannii*	*Picea pungens*
Pinus edulis / Juniperus spp.	C	C								
Quercus gambelii / Symphoricarpos oreophilus		o	C	o	o					
Pseudotsuga menziesii / Pachistima myrsinites		o		o	C	o		o	o	
Populus tremuloides / Symphoricarpos oreophilus						C		o		
Populus tremuloides / Pteridium aquilinum						C		o		
Populus tremuloides / Heracleum sphondyllium						C		o		
Populus tremuloides / Thalictrum fendleri						C		o	o	
Populus tremuloides / Carex geyeri						C		o		
Abies lasiocarpa / Vaccinium scoparium					o	s	S	C	C	
Abies lasiocarpa / Carex geyeri						S	s	C	C	
Picea pungens / Poa spp.					o	o				C

C = Climax; S = Major Seral; s = minor seral; o = occasional.

Figure 26.—The ecologic roles of tree species in habitat types of the White River National Forest.

Thalictrum fendleri, and *Populus tremuloides/Symphoricarpos oreophilus* habitat types are considered to be climatic climaxes. The *Populus tremuloides/Thalictrum fendleri* habitat type occupies soils apparently developed through normal processes throughout most of the zone. The *Populus tremuloides/Carex geyeri* habitat type is considered to be a topoedaphic climax and generally occupies drier south-facing sites with shallow soils at the upper edges of the zone. The *Populus tremuloides/Symphoricarpos oreophilus* habitat type normally occupies soils developed in place at lower and drier edges of the zone. Throughout most of the *Populus*-dominated zone, there are restricted areas where combinations of edaphic and topographic characteristics allow *Heracleum sphondylium*- and *Pteridium aquilinum*-dominated undergrowth to establish under *Populus*. Although *Populus tremuloides/Thalictrum fendleri* is the climatic climax throughout much of the *Populus* zone, undergrowth vegetation is expressed rather independently of the *Populus tremuloides* overstory.

In the *Abies lasiocarpa* zone, the two habitat types *Abies lasiocarpa/Vaccinium scoparium* and *Abies lasiocarpa/Carex geyeri*, are distinguished by differences in relatively few undergrowth species. However the two habitat types also show some topographic and elevational differences. Additionally, *Populus tremuloides* is an important seral species in the *Abies lasiocarpa/Carex geyeri* habitat type but only a minor seral species in the *Abies lasiocarpa/Vaccinium scoparium* habitat type. Conversely, *Pinus contorta* is an important seral species in the *Abies lasiocarpa/Vaccinium scoparium* habitat type but only a minor component of the *Abies lasiocarpa/Carex geyeri* habitat type.

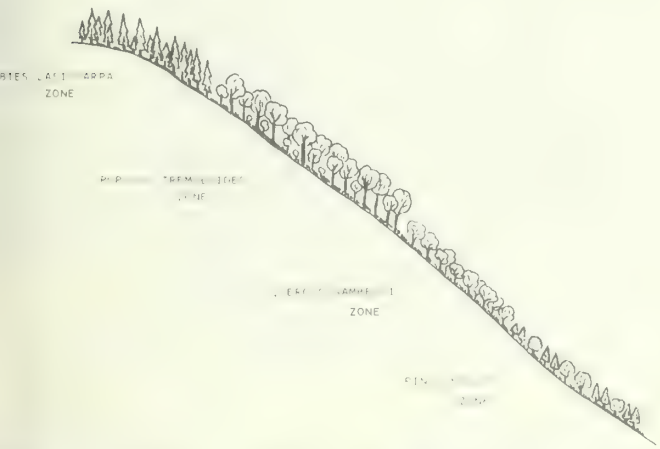
Distribution and Dynamics of Forest Tree Species

An example of the typical vegetation zonation on the White River National Forest—above Elk Creek to Cline tops northwest of Newcastle—is shown in figure 27

seudotsuga menziesii, which may grow above or below ne *Populus tremuloides* zone, is not shown, because *seudotsuga menziesii* is not widely distributed on the Vhite River National Forest. Neither is the *Artemisia ridentata* zone because this shrub-dominated steppe ccurs most often below the forest boundary.

Populus tremuloides is the most widely distributed ee on the White River National Forest. It reaches maxnum abundance at elevations from about 8,530 feet 600 m) to 10,000 feet (3050 m). At its upper elevational mits, *Populus tremuloides* extends into the *Abies siocarpa* zone. The role of *Populus tremuloides* as a eral and/or climax species has been discussed at length y Baker (1925), Dixon (1935), Fetherolf (1917), Gardner 905), Mueggler and Campbell (1982), Sampson (1925), nd Youngblood and Mueggler (1981). Most investiators have agreed that *Populus tremuloides* is an agressive species on areas that have been burned, gged, or otherwise disturbed; it reproduces primarily y root suckers. There is less agreement on the stability f *Populus tremuloides* once it is established. Data and bservations from the present study suggest that both eral and climax stands of *Populus tremuloides* occur in ne White River National Forest, as was observed in an arlier study on the Routt National Forest (Hoffman and lexander 1980). Seral *Populus* stands are quite obvious here *Abies lasiocarpa* and *Picea engelmannii* are the limax species. In *Abies*-dominated habitat types, either opulus *tremuloides* or *Pinus contorta* may become stablished first after disturbance, or they may estabsh simultaneously. The availability of *Pinus* seed or opulus root sprouts determines which species initially ecomes established.

Climax stands of *Populus tremuloides* show no clear vidence of successful conifer invasion. *Picea engelmanii* and *Pinus contorta* are rare in these stands, but an ccasional *Abies lasiocarpa* may occur. The presence of limited number of coniferous seedlings in the underowth is insufficient evidence of a successional trend, owever. In addition, *Populus* usually has a stable popuion structure. The understory vegetation of the opulus-dominated habitat types is distinct, although



igure 27.—Vegetation zonation above Elk Creek to Clinetops northwest of Newcastle.

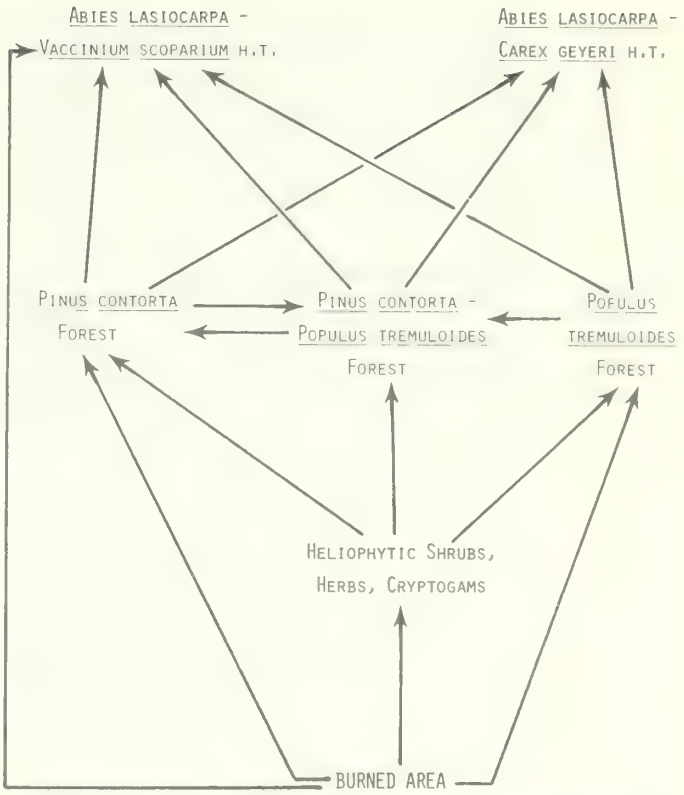

ABIES LASIOCARPA - VACCINIUM SCOPARIUM H.T.
ABIES LASIOCARPA - CAREX GEYERI H.T.
PINUS CONTORTA FOREST
PINUS CONTORTA - POPULUS TREMULOIDES FOREST
POPULUS TREMULOIDES FOREST
HELIOPHYTIC SHRUBS, HERBS, CRYPTOGAMS
BURNED AREA

Figure 28.—Pathways of secondary succession following fire in *Abies lasiocarpa-Picea engelmannii*-dominated vegetation in the White River National Forest.

common species occur between *Populus tremuloides*-dominated habitat types and other habitat types in the Forest. Some soils differences exist between *Populus*-dominated and *Abies*-dominated habitat types. The oldest stand of climax *Populus*-dominated habitat types on the White River National Forest was about 180 years old, and it is unknown if these trees are first generation after fire. If succession toward *Abies* and *Picea* forests is not evident in these stands, they should be viewed and managed as climax forests.

Abies lasiocarpa and *Picea engelmannii* dominate vegetation in the subalpine zone, which occurs from about 9,000 feet (2740 m) elevation to timberline. Neither species is important in other elevational zones. In the *Abies lasiocarpa/Vaccinium scoparium* habitat type, *Populus tremuloides* is not an important seral species compared to *Pinus contorta*. In the *Abies lasiocarpa/Carex geyeri* habitat type, the reverse seems to be true. On the basis of observations made during this study, figure 28 is suggested as a working model of succession following fire, in *Abies*-dominated forests, on the White River National Forest. From the population structures of seral communities, it appears that succession ordinarily follows one of the pathways shown in figure 28. This is somewhat different than secondary succession observed in the Routt National Forest (Hoffman and Alexander 1980). Following fire, in subalpine forests, on the White River National Forest, early successional communities are often a mixture of heliophytic shrubs, herbs, and cryptogams. In some localities, this stage of succession is prolonged, especially where the combina-

tion of a lack of seed source and/or root suckers and severe climate slow succession after large fires (fig. 29). Where abundant seeds and/or root suckers are available, fire can be followed promptly by *Populus tremuloides* and/or *Pinus contorta* regeneration. In some situations in the *Abies lasiocarpa/Vaccinium scoparium* habitat type, *Abies lasiocarpa*- and *Picea engelmannii*-dominated forests develop after fire without the seral stages of *Pinus contorta*, or *Populus tremuloides* (fig. 30). This successional trend has not been observed in *Abies lasiocarpa/Carex geyeri* habitat type, however. There also can be some shifting of dominance within the seral communities. On the White River National Forest, *Pinus contorta*-dominated forests may become *Pinus contorta/Populus tremuloides*-dominated forests, if *Populus* is present and *Pinus* does not fully occupy the site or *Pinus* stands begin to break-up. The reverse of this also happens with *Pinus-Populus*-dominated forests becoming *Pinus*-dominated forests. *Populus tremuloides*-dominated forests may add *Pinus contorta* before succession of *Abies*-dominated forests is completed, but *Pinus-Populus*-dominated forests usually do not lose the *Pinus* component before succeeding to *Abies*-dominated forests. In the case of succession on *Abies lasiocarpa/Carex geyeri* habitat types, most stands examined show evidence of going directly from *Populus*-dominated vegetation to *Abies*-dominated vegetation without *Pinus contorta*.

Pinus contorta forms no climax forests on the White River National Forest, although it is an important seral species over much of the *Abies lasiocarpa* zone. This observation is in contrast to its position on the Routt National Forest, where it is a climax species over a limited segment of its range and is an important seral species over much of the subalpine zone. It occurs also in numerous stands of *Populus tremuloides* (Hoffman and Alexander 1980). In the Crested Butte area to the south, Langenheim (1962) found seral *Pinus contorta* stands on burned areas, principally on north slopes with granitic or coarse textured soils, and at elevations of 9,500 feet (2,900 m) to 10,500 feet (3,200 m). In the Medicine Bow Mountains, *Pinus contorta* is an important seral species in *Abies lasiocarpa/Vaccinium scoparium* and *Abies lasiocarpa/Carex geyeri* habitat types. It also grows occasionally in stands dominated by *Populus tremuloides* (Wirsing and Alexander 1975).

The absence of a well-defined *Pseudotsuga* zone over much of the White River National Forest probably results from drought at low elevations and low temperatures at higher elevations. Moreover, *Pseudotsuga menziesii* shows little tendency to establish in areas now occupied by *Populus tremuloides*. Nor are there relicts of *Pseudotsuga menziesii* in *Populus tremuloides* stands to suggest it was formerly present.

Pinus ponderosa is rare, although an occasional old specimen grows in stands of *Pseudotsuga menziesii*- or *Quercus gambelii*-dominated vegetation. As indicated previously *Pinus ponderosa* has been nearly depleted by early logging and subsequent burning.

Quercus gambelii usually occupies xeric habitats in a zone below the *Populus tremuloides* zone. It often grows above or below the *Pinus edulis/Juniperus* spp. zone, and depending on slope and exposure it may also grow above *Populus tremuloides* (figure 31). *Quercus gambelii* and *Populus tremuloides* develop fewer mixed stands on the White River National Forest than grow on the Routt National Forest. Moisture may be a more limiting factor in the White River National Forest; where *Quercus* is abundant in the southwestern part of the Forest, there is little *Populus*.

Pinus edulis and *Juniperus* spp. have a limited distribution in the White River National Forest. Most stands dominated by these species grow below the lower boundaries of the Forest. It does not appear from limited observation that either *Pinus edulis* or *Juniperus* spp. move upslope into *Quercus gambelii*- or *Populus tremuloides*-dominated vegetation after sites have been disturbed. The only exception to this is an occasional specimen of *Juniperus scopulorum* growing in stands of *Pseudotsuga*- or *Quercus*-dominated vegetation.

Species Richness

The median numbers of undergrowth species in stands in each habitat type are given in table 2. Species richness is generally highest in the *Populus*-dominated habitat types and lowest in the *Abies*- and *Pseudotsuga*-dominated habitat types. In those habitat types that grow on both the White River and Routt National Forests, the median numbers of undergrowth species are quite similar, except for the *Pseudotsuga menziesii/Pachistima myrsinites* habitat type where the median numbers of undergrowth species was 21 on the White River National Forest and only 8 on the Routt National Forest. Tree species richness was highest on the *Abies* and *Pseudotsuga*-dominated habitat types and lowest on the *Pinus edulis/Juniperus* spp.- and *Populus*-dominated habitat types. With the exception of the *Populus tremuloides/Symphoricarpos oreophilus* habitat type *Populus*-dominated habitat types generally had fewer shrubs than *Abies*- and *Pseudotsuga*-dominated habitat types.

Species richness also has been reported for habitat types elsewhere in the Rockies. In the Wind River Mountains, it increased with increasing elevation (Reed 1969). In northern Idaho and eastern Washington, undergrowth species richness among climatic climaxes was greatest in mid-elevational habitat types dominated by *Pseudotsuga menziesii* and *Abies grandis*, and tree species richness was greatest in the *Abies lasiocarpa*-dominated habitat types (Daubenmire and Daubenmire 1968). In the Bighorn Mountains, greatest undergrowth species richness was in low and high elevation habitat types dominated by *Pinus ponderosa* and *Abies lasiocarpa*, respectively (Hoffman and Alexander 1976).

Further Studies in Relation to the Habitat Types

The present study was to provide a basic classification of the forest habitat types in the White River National Forest. There are numerous areas of research which logically follow this study.

Figure 29.—Slow regeneration of *Abies lasiocarpa* and *Picea engelmannii* following an apparently extensive fire and salvage logging on White River Plateau. The dense herbaceous vegetation may compete effectively with germination and establishment of conifers.

Figure 30.—On this roadcut, *Picea engelmannii* is becoming established on bad mineral soil.

Figure 31.—Vegetation zonation above Elk Creek north of Newcastle.

Table 2. Species of undergrowth vegetation in habitat types of the White River National Forest

Habitat type	Median number[1] of undergrowth species	Number of stands studied
Pseudotsuga menziesii / Pachistima myrsinites	21	2
Populus tremuloides / Symphoricarpos oreophilus	27	8
Populus tremuloides / Thalictrum fendleri	26	12
Populus tremuloides / Pteridium aquilinum	35	1
Populus tremuloides / Heracleum sphondyllium	20	2
Populus tremuloides / Carex geyeri	21	4
Abies lasiocarpa / Vaccinium scoparium	16	17
Abies lasiocarpa / Carex geyeri	22	5

[1]*Based on 125 m² per stand*

The production of undergrowth vegetation in relation to habitat types needs to be examined. Ellison and Houston (1958), working in Utah, suggested that production of vegetation under *Populus tremuloides* could be used as an indicator of forage production and, therefore, range condition. In the White River National Forest, both cattle and sheep utilize, sometimes quite heavily, vegetation under *Populus*. It would be valuable to know the relationship between habitat types and potential undergrowth productivity.

The growth rates of important timber trees may correlate with habitat types similar to the relationship of growth rates of *Pinus ponderosa* and the habitat types in the northern Rocky Mountains described by Daubenmire (1961).

Numerous fungi attack *Populus tremuloides* in Colorado (Juzwik et al. 1978). Some *Populus* habitat types may be more susceptible to various species of fungi than others are. In northern Idaho and eastern Washington, *Arceuthobium* infects *Pinus ponderosa* in the *Pinus ponderosa/Agropyron spicatum* and *Pinus ponderosa/Purshia tridentata* habitat types, but not in other habitat types dominated by *Pinus ponderosa* (Daubenmire 1961). Susceptibility of *Picea engelmannii* to insect infestation may be correlated with habitat types in Colorado (Shepherd 1959).

The relationship of forest habitat types and their successional stages to wildlife management also needs further research.

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Appendix

Table A-1.—Tree population structures for each habitat type. Numbers of trees listed are based on sample plot data for 375 m² per stand

Habitat type and species	Stands sampled	Mean basal area	Diameter (d.b.h.) classes in dm									
			0.1									
			<0.5	>0.5	1-2	2-3	3-4	4-5	5-6	7-7	>8	
	number	*m²/ha*	..... *number of trees*									
Pseudotsuga menziesii/												
Pachistima myrsinites	2	30.9										
Pseudotsuga menziesii			18	6	21	12	2					
Picea engelmannii			2									
Abies lasiocarpa					(1)							
Juniperus scopulorum			8	2	1							
Populus tremuloides/												
Symphoricarpos oreophilus	8	41.8										
Populus tremuloides			83	29	20	10	7	2	(1)			
Abies lasiocarpa				(1)								
Populus tremuloides/												
Thalictrum fendleri	12	49.2										
Populus tremuloides			175	14	12	12	7	1	(1)	(1)		
Abies lasiocarpa			(1)	(1)								
Populus tremuloides/												
Pteridium aquilinum	1	29.3										
Populus tremuloides			240	9	6	7	6					
Populus tremuloides/												
Heracleum sphondylium	2	36.5										
Populus tremuloides			124	10	-	9	7	2				
Populus tremuloides/												
Carex geyeri	4	37.4										
Populus tremuloides			193	5	19	13	4					
Abies lasiocarpa				(1)								
Abies lasiocarpa/												
Carex geyeri	5	58.7										
Abies lasiocarpa			87	10	5	1	(1)	(1)		(1)		
Picea engelmannii			9	2	3	1	3	4	1	(1)	(1)	(1)
Populus tremuloides			6	2	5	5	2	(1)				
Abies lasiocarpa/												
Vaccinium scoparium	17	54.3										
Abies lasiocarpa			103	5	5	2	1	(1)				
Picea engelmannii			21	2	5	2	1	1	1	(1)	(1)	
Pinus contorta			3	3	6	8	3	1				
Populus tremuloides			(1)	(1)	2	1						

[1] *Species with less than 1 per d.b.h. class.*

Table A-2.—Location, topographic position, coverage (percent), and frequency (percent) of undergrowth species in stands of the *Pseudotsuga menziesiilPachistima myrsinites* habitat type

	Stand number	
	36	57
Location		
Section	**17**	**20**
Township	**8S**	**8S**
Range	**83W**	**83W**
Topographic position		
Slope (%)	**56**	**64**
Aspect (°)	**266**	**290**
Elevation (m)	**2560**	**2697**
	Coverage[1]/Frequency	
Shrubs		
Acer glabrium	1.1/8	-
Amelanchier alnifolia	-	0.8/6
Clematis pseudoalpina	-	1.5/10
Juniperus communis	+ /2	3.1/16
Juniperus scopulorum	-	2.1/4
Mahonia repens	-	3.0/28
Pachistima myrsinites	35.0/88	21.0/76
Ramischia secunda	+ /2	-
Rosa sp.	3.2/30	3.8/28
Shepherdia canadensis	+ /2	1.4/8
Symphoricarpos oreophilus	1.7/8	4.6/20
Graminoids		
Calamagrostis rubescens	0.5/10	-
Carex geyeri	2.1/12	2.6/20
Poa spp.	+ /2	-
Forbs		
Antennaria microphylla	+ /6	-
Aquilegia caerulea	1.1/20	-
Arnica cordifolia	1.4/10	+ /4
Epilobium angustifolium	+ /2	0.5/6
Fragaria sp.	+ /2	+ /2
Galium boreale	-	0.9/10
Lathyrus leucanthus	+ /2	-
Mosses + Lichens	14.0/56	27.0/78
Osmorhiza depauperata	+ /2	+ /2
Pseudocymopterus montanus	+ /8	-
Senecio wootonii	0.8/8	-
Smilacina racemosa	-	+ /4
Solidago multiradiata	1.6/16	+ /6
Solidago spathulata	-	0.5/6

[1] *+ indicates coverage of less than 0.5%.*

Table A-3.—Location, topographic position, coverage (percent), and frequency (percent) of undergrowth species in stands of the *Populus tremuloides/Symphoricarpos oreophilus*, *Populus tremuloides/Heracleum sphondylium*, and *Populus tremuloides/Carex geyeri* habitat types

	Stand number													
	Populus/Symphoricarpos H.T.								*Populus/ Heracleum* H.T.		*Populus/ Carex* H.T.			
	4	10	48	6	7	37	38	19	35	54	25	26	27	41
Location														
Section	6	34	32	11	11	8	5	24	30	17	14	14	10	26
Township	4S	3S	1S	11S	11S	8S	8S	5S	4S	7S	8S	8S	8S	8S
Range	91W	92W	91W	89W	89W	83W	83W	82W	90W	83W	83W	83W	83W	83W
Topographic position														
Slope (%)	25	—	—	—	—	34	30	30	22	42	38	38	30	43
Aspect (°)	85	—	—	—	—	265	82	66	156	154	174	176	180	170
Elevation (m)	2652	2752	2667	2774	2774	2758	2858	2591	2713	2957	2975	2975	3033	2972
	Coverage[1]/Frequency													
Shrubs														
Amelanchier alnifolia	—	5.7/20	—	—	—	—	1.2/10	5.8/34	—	—	+ /6	+ /2	—	2.5/4
Abies lasiocarpa	—	—	—	3.7/6	—	—	—	—	—	—	—	—	—	—
Mahonia repens	—	—	—	—	—	—	—	3.2/16	—	—	—	+ /2	0.5/8	—
Pachistima myrsinites	—	—	—	—	—	—	2.9/8	—	—	—	1.1/8	—	+ /2	—
Populus tremuloides	—	—	—	3.2/12	+ /2	2.1/16	—	—	1.1/8	0.5/8	8.3/28	—	—	—
Prunus virginiana	—	+ /2	—	—	—	—	—	7.5/32	—	—	—	—	—	7.4/12
Rosa sp.	—	0.5/8	—	—	1.7/8	7.1/36	3.0/22	5.4/30	—	—	4.5/36	8.1/38	1.7/18	—
Salix scouleriana	—	—	—	—	—	—	—	—	—	—	—	—	+ /2	—
Sambucus racemosa	—	—	—	—	—	—	+ /2	0.6/4	—	—	—	—	—	—
Sorbus scopulina	—	—	—	2.2/4	+ /2	—	—	0.6/4	8.0/30	—	—	—	—	—
Symphoricarpos oreophilus	30.0/82	35.0/70	7.0/32	34.0/70	29.0/78	23.0/52	22.0/48	6.2/12	2.1/2	1.6/2	2.1/10	—	—	0.7/8
Graminoids														
Bromus anomalus	—	—	0.6/6	—	—	—	—	1.3/12	—	—	—	—	—	—
Bromus ciliatus	2.3/16	1.7/18	18.0/76	—	—	+ /6	2.3/18	8.4/54	20.0/80	8.0/32	4.6/40	1.1/8	0.8/6	2.6/24
Calamagrostis rubescens	3.5/8	—	—	—	—	—	—	—	—	—	—	—	—	3.0/8
Carex geyeri	27.0/62	30.0/92	25.0/68	46.0/86	36.0/100	49.0/100	39.0/100	43.0/96	—	32.0/80	39.0/98	40.0/100	29.0/96	42.0/92
Elymus glaucus	3.3/20	9.6/40	1.9/16	5.1/42	9.6/62	1.4/18	6.6/26	21.0/78	6.7/40	3.6/12	11.0/68	6.8/30	2.3/20	14.0/60
Festuca thurberi	—	—	—	—	—	—	—	—	—	—	—	—	—	2.3/6
Melica spectabilis	+ /2	—	—	—	—	—	—	—	—	—	—	—	—	—
Poa interior	4.2/26	—	+ /4	—	—	—	—	—	3.1/18	—	+ /2	12.0/38	4.8/20	—
Poa nevadensis	—	—	—	—	—	—	—	—	—	—	—	—	2.3/12	—
Poa pratensis	4.6/22	—	—	—	—	—	—	—	—	—	—	10.0/24	—	+ /2
Forbs														
Achillea millefolium	9.4/60	4.8/36	1.9/16	—	—	3.6/26	—	1.2/26	1.4/10	+ /6	4.3/50	5.4/42	4.8/36	1.0/20
Agastache urticifolia	4.8/16	—	0.7/8	—	—	—	—	—	—	—	—	—	—	—
Aquilegia caerulea	—	1.1/8	—	4.9/20	1.4/8	+ /4	—	—	2.5/16	0.6/10	—	—	—	—
Arnica cordifolia	—	—	—	—	—	—	—	+ /8	—	—	6.6/64	2.9/28	6.9/58	—
Arnica parryi	—	—	12.0/44	—	—	—	—	—	—	—	—	—	—	—
Aster engelmannii	—	1.1/20	—	2.7/36	2.9/18	8.0/52	6.4/20	1.5/4	0.2/8	+ /4	—	—	2.8/28	—
Castilleja sulphurea	—	—	—	—	—	3.1/18	0.8/8	—	—	—	—	—	1.6/14	0.7/8
Chenopodium atrovirens	0.5/10	—	—	—	—	—	—	—	+ /2	+ /2	—	—	—	—
Cirsium sp	0.9/4	—	3.4/20	+ /4	—	—	1.2/10	2.3/32	1.7/8	—	—	—	—	10.0/40
Clematis pseudoalpina	—	—	—	—	—	—	—	0.6/4	—	—	—	—	—	—
Collomia linearis	—	—	—	—	—	—	—	0.7/8	—	—	+ /2	—	—	—
Delphinium barbeyi	—	+ /2	—	+ /6	—	5.8/20	+ /2	—	—	+ /2	—	—	—	—
Descurainia californica	0.8/6	—	—	—	—	—	—	—	+ /2	+ /2	—	—	—	—
Dugaldia hoopesii	7.8/36	+ /2	—	—	—	3.6/12	21.0/58	—	—	—	2.1/22	+ /2	—	+ /4
Epilobium angustifolium	—	—	—	—	—	+ /2	2.4/22	1.9/16	—	3.6/32	+ /4	0.5/8	+ /2	0.7/8
Erigeron elatior	0.8/6	—	—	+ /4	1.1/8	—	2.3/18	—	—	+ /2	—	0.8/6	—	—
Erigeron speciosus	—	—	—	—	—	+ /2	—	—	—	—	—	—	+ /2	—
Fragaria sp	2.0/18	—	5.5/28	4.8/48	+ /6	1.4/18	1.4/18	2.1/46	—	—	3.9/42	+ /18	16.0/72	36.0/88
Galium aparine	—	—	—	—	—	—	—	7.5/24	—	—	—	—	—	—
Galium boreale	2.9/28	2.1/26	0.8/12	1.5/22	2.5/38	+ /12	+ /10	+ /4	—	—	—	—	—	—
Geranium caespitosum	0.5/8	—	—	—	—	—	—	—	—	—	—	—	—	—
Geranium richardsonii	2.7/12	0.9/10	32.0/96	0.9/26	+ /2	2.8/28	2.8/40	1.3/12	4.5/32	23.0/70	—	—	—	+ /8
Heracleum sphondylium	—	—	—	—	—	+ /2	—	—	67.0/92	48.0/90	—	—	—	—
Hydrophyllum capitatum	+ /2	—	0.9/20	—	—	—	—	—	—	—	—	—	—	—
Lathyrus leucanthus	14.0/58	13.0/66	2.5/20	25.0/78	23.0/88	12.0/50	15.0/68	4.8/24	—	—	13.0/56	18.0/86	24.0/82	15.0/52
Ligusticum porteri	0.8/6	2.0/8	—	5.0/10	5.0/12	8.2/28	8.8/30	—	—	—	—	—	—	—
Lupinus argenteus	—	16.0/60	—	+ /2	—	6.7/30	+ /2	+ /8	—	—	+ /6	—	7.0/60	—
Mertensia ciliata	—	—	—	0.6/12	+ /2	—	—	—	—	—	—	—	—	—
Nemophila breviflora	5.0/30	—	—	—	—	—	—	—	—	—	—	—	—	—
Osmorhiza occidentalis	—	—	0.6/6	—	—	1.2/8	—	+ /2	—	2.3/12	—	—	—	—
Osmorhiza sp.	0.8/6	8.2/66	9.3/44	12.0/62	3.3/32	—	—	3.4/58	35.0/62	+ /2	—	—	—	—
Pedicularis procera	—	+ /2	—	—	—	—	—	—	—	—	—	—	—	—
Penstemon strictus	—	—	—	1.6/12	—	—	—	—	—	—	—	—	—	—
Potentilla gracilis	+ /2	—	—	—	—	—	—	—	—	—	—	—	—	—
Pseudocymopterus montanus	—	—	—	—	—	—	—	—	—	—	+ /2	+ /2	—	—
Polemonium caeruleum	—	—	—	0.8/4	—	—	—	—	0.8/4	—	—	—	—	—
Rudbeckia laciniata	—	—	6.7/20	—	—	—	—	—	—	—	—	—	—	—
Senecio serra	—	—	13.0/40	1.4/18	—	+ /2	—	—	3.3/12	8.2/30	—	—	—	+ /8
Smilacina racemosa	4.0/18	—	—	—	1.1/8	—	—	—	—	—	2.3/30	2.0/18	+ /2	—
Stellaria jamesiana	12.0/68	0.8/8	2.7/28	—	—	+ /2	+ /2	—	10.0/58	—	—	—	—	—
Streptopus amplexifolius	—	+ /2	—	—	—	—	—	—	—	—	—	—	—	—
Taraxacum sp	1.9/16	+ /2	0.7/8	3.6/42	0.8/8	+ /6	+ /6	0.7/8	—	—	—	+ /2	—	5.4/40
Thalictrum fendleri	11.0/42	23.0/66	25.0/80	12.0/40	31.0/80	37.0/88	27.0/92	4.4/12	14.0/42	43.0/96	20.0/58	13.0/52	1.1/8	11.0/24
Thlaspi montanum	—	—	1.2/12	—	—	—	—	—	—	—	—	—	—	—
Valeriana occidentalis	—	+ /2	—	+ /8	1.4/18	1.2/10	—	+ /4	—	—	—	—	—	—
Vicia americana	4.8/32	5.3/30	0.7/8	13.0/68	22.0/86	15.0/58	27.0/80	2.9/24	—	29.0/78	30.0/88	18.0/76	6.8/32	32.0/92
Viola canadensis	4.9/48	+ /10	—	1.2/22	+ /6	—	+ /2	—	—	2.5/26	—	—	—	—
Viola nuttallii	—	—	—	—	—	—	—	+ /4	—	1.2/10	—	—	—	—

[1] + indicates coverage of less than 0.5%.

Table A-4.—Location, topographic position, coverage (percent), and frequency (percent) of undergrowth species in the *Populus tremuloides/Thalictrum fendleri* and *Populus tremuloides/Pteridium aquilinum* habitat types

	Stand number												
	Populus/Thalictrum H.T.												*Populus/ Pteridium* H.T.
	2	3	11	16	34	24	15	5	53	39	40	18	14
Location													
Section	33	24	20	30	32	23	2	21	17	30	25	25	1
Township	3S	3S	3S	3S	3S	8S	11S	7S	7S	4S	4S	5S	11S
Range	92W	93W	92W	92W	90W	90W	89W	93W	83W	87W	88W	82W	89W
Topographic position													
Slope (%)	15	—	20	8	17	30	10	40	40	—	10	15	—
Aspect (°)	56	—	50	120	106	114	155	186	166	—	150	346	—
Elevation (m)	2736	2858	2781	2682	2957	2877	2560	2865	3002	3033	3048	2619	2682
	Coverage[1]/Frequency												
Shrubs													
Abies lasiocarpa	—	—	—	—	—	—	—	—	4 8/6	—	—	—	—
Amelanchier alnifolia	—	—	—	—	—	—	3 6/12	—	—	—	—	—	—
Pachistima myrsinites	—	—	+ /4	—	—	—	—	+ /2	—	—	—	—	—
Populus tremuloides	3 9/35	—	+ /2	1.3/16	+ /2	—	—	—	+ /6	4.8/24	—	+ /4	5 8/28
Rosa sp.	—	—	+ /6	0 7/8	—	—	1 3/12	—	—	—	—	—	—
Rubus parviflorus	—	—	—	—	—	—	—	—	—	—	—	2.0/8	—
Sambucus racemosa	—	—	—	—	—	+ /2	—	—	—	—	—	2.0/8	—
Symphoricarpos oreophilus	7.3/22	3 7/12	6 1/20	9.3/23	—	—	14 0/40	—	—	—	—	—	5 3/18
Graminoids													
Bromus anomalus	—	—	—	2 3/10	—	1 8/8	3 7/10	—	—	—	2 9/12	3 0/22	—
Bromus ciliatus	7 8/72	5 6/62	4 3/22	16 0/74	1 8/12	11 0/70	—	+ /2	9 1/36	0 8/12	1 2/8	5 1/50	1 5/10
Calamagrostis rubescens	—	+ /2	—	—	—	—	—	—	—	—	—	—	1 0/6
Carex geyeri	4.7/20	6.5/22	20.0/72	19.0/80	—	0.7/4	59.0/92	30.0/80	41.0/92	25.0/60	2.7/12	24.0/74	4.9/28
Carex spp.	—	—	—	—	—	—	—	—	—	—	—	—	+ /2
Elymus glaucus	8 0/52	5 2/40	27 0/88	7 8/50	7 2/60	+ /4	16 0/70	1 9/6	+ /2	9 9/32	0 7/8	11 0/62	7 9/40
Melica spectabilis	—	1 1/24	—	—	5 2/42	2 4/10	—	—	—	—	—	—	—
Poa agassizensis	—	—	—	+ /4	—	—	+ /8	—	—	—	—	+ /6	—
Poa leptocoma	—	+ /2	—	—	—	—	+ /4	—	—	—	—	—	—
Poa pratensis	—	—	—	—	—	+ /4	—	—	0 9/6	—	—	+ /2	—
Poa trivalis	—	—	—	—	—	—	—	—	—	—	—	+ /2	—
Forbs													
Achillea millefolium	—	+ /2	—	7 5/42	—	—	+ /8	—	—	—	—	3 2/50	2 9/28
Actaea rubra	—	—	—	—	—	—	—	—	—	—	—	—	0 9/4
Agastache urticifolia	+ /2	—	—	—	3.2/12	—	—	—	—	—	—	—	—
Androsace septentrionalis	—	—	—	—	+ /2	—	—	—	—	—	—	—	—
Aquilegia caerulea	0 8/8	+ /4	0 7/6	—	2 2/26	+ /4	—	1 7/10	—	+ /12	+ /10	—	—
Arnica cordifolia	—	—	—	—	—	—	—	—	—	—	—	+ /16	—
Arnica parryi	—	—	—	—	—	+ /4	—	—	+ /2	—	—	—	—
Aster engelmannii	4.0/18	3.6/26	6.3/50	—	5.3/10	2.5/16	3.1/46	+ /2	0.9/12	2.3/16	—	+ /4	3.8/20
Castilleja sulphurea	—	—	—	—	—	—	—	—	—	—	—	0.9/16	—
Cerastium arvense	—	+ /2	—	—	—	—	—	—	—	—	—	—	—
Chenopodium atrovirens	—	+ /2	—	—	—	—	+ /4	—	—	—	—	—	—
Cirsium sp.	+ /6	+ /4	+ /2	0 7/8	3 4/38	+ /6	—	—	—	—	+ /4	2 5/24	+ /2
Collomia linearis	—	—	+ /2	—	—	—	—	—	—	—	—	—	—
Delphinium barbeyi	0 7/6	—	0 6/14	—	—	0 8/6	—	—	1 1/8	—	18 0/36	—	1 4/10
Descurainia californica	—	—	—	0 7/8	—	—	—	—	—	—	—	—	—
Draba sp.	—	1.1/14	—	—	—	—	—	—	—	—	—	—	—
Dugaldia hoopesii	—	3 7/14	—	—	4 8/28	—	—	0 6/4	—	0 6/4	—	—	—
Epilobium angustifolium	+ /2	0 9/6	+ /2	3 3/20	—	—	—	12 0/52	20 0/86	—	1 4/16	0 6/4	0 4/6
Erigeron elatior	—	0 7/6	—	—	—	—	—	0 9/8	—	+ /4	0 6/4	3 4/24	+ /4
Erigeron speciosus	—	—	+ /4	—	—	0 5/6	—	—	—	—	—	+ /4	—
Fragaria sp.	+ /6	3 3/32	1 3/14	—	—	+ /2	+ /8	+ /6	—	+ /8	—	6 7/80	4 8/42
Galium aparine	—	—	—	—	+ /4	—	—	—	—	—	—	—	—
Galium boreale	0 9/10	0 9/6	0 8/20	4 4/62	—	2 9/30	0 6/24	—	—	—	—	4 6/70	5 1/68
Geranium richardsonii	4 8/32	3 2/24	11 0/62	4 4/46	—	0 6/10	—	34 0/90	25 0/75	8 8/64	0 9/16	11 0/58	3 9/38
Heracleum sphondylium	7 7/45	+ /2	+ /2	0 6/4	—	10 0/50	—	8 2/28	11 0/28	—	—	—	8 2/20
Hydrophyllum capitatum	2 9/20	5 6/30	2 1/12	—	+ /2	15 0/60	—	—	—	—	—	—	—
Hydrophyllum fendleri	3 6/24	—	—	—	—	—	+ /2	—	—	—	+ /4	—	—
Lathyrus leucanthus	15 0/48	2.5/14	10.0/42	9 0/46	6.6/36	0.8/8	3.7/32	22.0/70	2.6/12	32 0/80	0.8/12	14.0/70	9.0/48
Ligusticum porteri	—	60 0/90	12 0/20	—	26 0/60	27 0/58	8 8/28	—	—	50 0/72	52 0/76	—	—
Lupinus argenteus	1 9/16	2 6/18	7 4/46	0 6/16	—	—	10 0/54	1 3/22	—	/5	—	5 5/46	—
Mertensia ciliata	—	—	—	—	—	—	—	—	—	9 0/56	18 0/72	—	+ /2
Nemophila breviflora	—	—	—	—	+ /2	9 0/42	—	—	—	—	—	—	—
Osmorhiza occidentalis	—	—	5 9/20	5 1/34	—	—	5 7/28	—	—	—	—	2 0/18	1 3/6
Osmorhiza sp.	15.0/52	17.0/44	4.4/26	13.0/70	36.0/78	25.0/80	8.8/54	—	—	0.6/4	26 0/64	5.0/66	13.0/50
Pedicularis bracteosa	—	+ /2	0 6/4	—	—	—	—	9 0/34	—	18 0/32	—	—	—
Pedicularis procera	+ /2	—	—	—	—	—	—	1.0/12	1.3/6	—	—	—	—
Penstemon whippleanus	—	—	—	+ /2	—	—	—	—	—	—	—	—	—
Phacelia heterophylla	—	—	—	+ /4	—	—	—	—	—	—	—	—	—
Polemonium caeruleum	—	—	—	—	—	5 1/18	—	—	—	—	—	—	+ /2
Potentilla gracilis	—	—	—	—	—	—	—	—	—	—	—	—	+ /4
Pteridium aquilinum	—	—	—	—	—	—	—	—	—	—	—	—	78 0/96
Rudbeckia laciniata	—	—	7.1/34	—	—	—	—	—	—	—	—	—	4.3/22
Senecio crassulus	—	—	—	7 0/42	—	—	—	1 3/10	—	—	—	—	—
Senecio serra	—	—	+ /2	1.0/20	3.6/22	+ /6	—	2.1/8	3.8/20	4.1/28	8.0/38	2.4/24	+ /2
Smilacina racemosa	0.7/6	—	—	—	—	—	—	0.9/6	5.7/28	—	—	—	0.9/4
Smilacina stellata	—	—	—	+ /8	—	—	—	—	—	—	—	—	—
Solidago spathulata	—	—	—	—	—	—	—	—	—	—	—	3.6/32	—
Stellaria jamesiana	17 0/78	12.0/70	5.4/60	4.3/42	12.0/92	4.3/28	—	+ /2	—	1.1/24	9.0/64	—	—
Streptopus amplexifolius	—	—	—	—	—	—	—	—	—	—	—	—	+ /4
Taraxacum sp.	—	—	+ /2	+ /8	—	—	0 7/8	+ /2	+ /2	—	—	0 9/16	2 1/22
Thalictrum fendleri	21.0/58	6.6/24	45.0/88	18.0/54	19.0/48	1.9/8	36 0/92	24.0/84	37.0/100	21.0/68	59.0/88	7.1/12	8.5/18
Thlaspi montanum	—	—	—	—	0 5/8	—	—	—	—	—	+ /4	—	—
Trillium ovatum	—	—	—	—	+ /8	4 0/36	—	—	—	—	—	—	—
Valeriana occidentalis	0 7/6	4 0/16	3 2/24	—	6 3/25	9 2/36	+ /4	4 1/24	+ /2	1 3/12	1 2/8	—	+ /2
Veratrum tenuipetalum	—	—	—	—	—	0 5/6	—	—	—	—	—	—	—
Vicia americana	3.1/16	1.0/8	4.9/30	8.8/54	—	+ /2	32.0/70	14.0/64	25.0/70	30.0/64	—	9.4/58	8.1/36
Viola canadensis	—	—	+ /2	—	—	—	—	1 3/10	0 9/10	—	—	—	1 9/28
Viola nuttallii	—	0 7/8	—	0 5/20	—	+ /2	0 6/4	7 1/60	4 8/58	5 5/48	1 4/36	—	2 8/24
Wyethia amplexicaulis	—	—	—	—	—	—	—	—	—	0 6/4	—	—	—

[1] + indicates coverage of less than 0.5%

Table A-5.—Location, topographic position, coverage (percent), and frequency (percent) of undergrowth species in the *Abies lasiocarpa/Vaccinium scoparium* habitat type

	Stand number																
	9	50	51	1	55	12	28	13	42	22	23	47	46	52	21	20	45
Location																	
Section	12	21	5	6	21	25	15	31	23	3	1	14	20	30	17	17	2
Township	11S	9S	9S	9S	8S	8S	8S	8S	6S	6S	6S	4S	4S	4S	4S	4S	6S
Range	89W	84W	84W	84W	82W	82W	83W	82W	83W	80W	80W	81W	81W	80W	81W	81W	80W
Topographic position																	
Slope (%)	25	40	—	12	33	27	38	30	12	27	19	20	20	25	35	12	15
Aspect (°)	320	286	—	292	176	196	326	190	273	286	86	286	4	292	326	26	181
Elevation (m)	2743	2972	3048	3231	2896	2972	3050	3078	2941	3261	3414	2896	2957	3048	3063	3078	3353
	Coverage[1]/Frequency																
Shrubs																	
Abies lasiocarpa	8 4/28	0.8/12	5 5/12	3 6/20	—	—	—	—	1 6/6	—	6 2/16	4 4/24	—	—	—	+ /2	+ /2
Juniperus communis	—	2.4/4	—	—	—	—	—	0.7/2	2.0/8	—	—	—	—	—	—	—	—
Mahonia repens	—	—	—	—	+ /2	0 8/4	—	+ /4		—	—	—	—	—	—	—	—
Pachistima myrsinites	+ /6	12.0/56	—	—	+ /8	0 8/14	+ /2	0 5/10	3 1/28	—	—	+ /6	+ /4	1 0/20	0 8/10	+ /6	—
Picea engelmannii	—	2 1/8	—	1 8/6	—	—	+ /2	—	—	—	—	+ /4	—	—	—		—
Ramischia secunda	—	0 6/4	—	—	—	—	0 9/10	—	0 9/10	2 4/20	+ /2	—	+ /12	—	1 6/14	+ /2	-
Rosa sp.	—	—	—	—	1.7/28	1.8/34	0.5/8	4.6/42	+ /2	—	—	—	—	—	—	—	—
Rubus parviflorus	+ /2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Shepherdia canadensis	—	—	—	—	—	4.9/10	—	14 0/26	—	—	—	+ /4	—	4.0/8	—	—	—
Sorbus scopulina	—	—	—	+ /2	—	—	—	—	—	—	—	—	—	-	—	—	—
Symphoricarpos oreophilus	0 9/4	—	—	—	—	—	—	—	—	—	—	—	—		—	—	—
Vaccinium cespitosum	—	—	—	—	—	—	+ /2	—	—	—	1 7/12	—	—	—	—	—	—
Vaccinium myrtillus	2 1/12	—	0 7/6	16 0/50	—	0 6/4	7 4/52	+ /2	11 0/72	1 7/12	19 0/76	6 8/56	1 3/12	1 5/20	11 0/72	7 5/42	11 0/68
Vaccinium scoparium	15 0/58	49 0/92	77 0/100	30 0/72	30 0/76	21 0/88	42 0/98	28 0/80	12 0/78	5 2/32	25 0/82	70 0/100	34 0/88	43 0/100	37 0/98	35 0/96	60 0/100
Graminoids																	
Bromus ciliatus	+ /4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Calamagrostis inexpansa	—	+ /4	—	—	—	—	—	—	+ /2	0 7/8	—	—	—	—	—	—	—
Carex geyeri	+ /2	—	6.4/40	1 4/8	9.8/44	0 7/2	—	+ /8	—	0 6/6	13 0/46	—	—	—	+ /2	5 4/32	23 0/64
Elymus glaucus	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	+ /4	—
Poa nemoralis	—	—	—	—	+ /2	—	—	—	—	+ /4	-	—	0 5/14	—	—	—	—
Poa nervosa	+ /2	—	—	—	—	—	+ /6	—	—	—	—	—	2 7/28	—	—	—	+ /4
Poa pratensis	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	+ /4	—
Forbs																	
Achillea millefolium	—	—	—	+ /2	—	—	—	+ /2	—	—	—	—	—	—	—	—	—
Antennaria microphylla	—	—	—	—	—	+ /2	—	—	—	—	—	—	—	—	—	—	—
Arnica cordifolia	5.5/50	9.0/56	0.6/8	0 7/18	0 6/6	3.6/32	1 0/18	1 0/22	12 0/66	14 0/88	3 0/36	—	5 7/36	1 1/24	10 0/58	21 0/64	4 4/24
Arnica latifolia	—	—	—	—	—	—	—	—	—	+ /2	—	—	—	—	—	—	—
Aster engelmannii	0.9/10	—	—	—	—	—	—	—	—	—	—	—	2.9/36	—	—	+ /2	—
Campanula rotundifolia	—	—	—	—	—	+ /6	—	—	—	—	—	—		—	—	+ /2	—
Castilleja culphurea	—	—	—	—	—	—	—	—	+ /2	—	—	—	—	—	—	—	—
Epilobium angustifolium	—	0.9/16	—	+ /4	—	+ /2	+ /6	+ /2	+ /2	—	—	—	+ /4	—	—	0 9/6	—
Erigeron peregrinus	—	0.6/4	—	—	—	—	—	+ /4	—	—	+ /2	—	—	—	—	+ /2	—
Fragaria sp.	—	—	—	+ /4	—	—	+ /2	1 9/28	—	0 7/8	—	—	—	—	—	—	—
Galium boreale	1 1/18	—	—	—	—	+ /2	—	—	—	+ /2	—	—	—	+ /2	—	—	—
Hieracium albiflorum	—	—	—	+ /2	0.8/12	+ /6	—	—	—	—	—	—	—	—	—	+ /2	—
Lathyrus leucanthus	—	5.3/40	—	—	—	—	—	—	11 0/30	—	—	0 8/12	8 7/44	6 0/48	3 2/28	8 0/40	—
Ligusticum porteri	—	—	—	—	—	—	—	—	—	2.1/14	—	—	—	—	—	—	—
Lupinus argenteus	—	0.8/12	—	4 5/32	—	—	+ /2	—	—	—	4.9/32	—	5 1/68	—	—	—	1 2/8
Mertensia ciliata	—	—	—	—	—	—	—	—	—	5.6/28	—	—	—	—	—	—	—
Mosses + Lichens	1.0/16	—	1.9/16	10.0/36	1.1/24	+ /4	7.4/40	—	+ /10	5.8/20	1.5/10	20 0/64	5.6/32	5.0/48	16.0/52	+ /2	0.8/12
Osmorhiza depauperata	+ /6	—	—	+ /2	—	—	—	+ /2	—	4 6/28	—	—	—	—	—	—	—
Pedicularis racemosa	—	+ /12	11.0/44	—	—	—	—	—	—	+ /2	11 0/38	+ /2	+ /12	—	0 7/6	+ /2	8 2/24
Polemonium caeruleum	—	—	—	+ /2	—	—	—	—	—	1 3/12	—	—	—	—	—	+ /2	—
Potentilla gracilis	—	+ /2	—	—	—	—	+ /4	—	—	+ /4	—	—	—	—	+ /4	—	—
Pseudocymopterus montanus	+ /2	—	—	—	+ /2	—	—	+ /4	—	—	—	+ /2	—	—		+ /2	
Senecio serra	—	—	—	—	—	+ /12	—	—	2 4/18	—	—	—	—	—	—	+ /2	—
Senecio wootonii	—	—	—	—	—	—	+ /6	—	—	—	—	—	+ /4	—	-	—	—
Smilacina racemosa	+ /2	0.6/8	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Solidago multiradiata	—	0.9/16	—	0.5/8	+ /4	2.8/34	—	2.1/26	3.4/30	—	—	—	+ /4	—	—	+ /8	—
Solidago spathulata	—	—	—	+ /4	—	—	—	+ /6	—	—	0 5/12	—	—	—	—	—	+ /6
Vicia americana	—	—	—	—	—	—	—	—	0.8/20	—	—	—	0.4/16	1.2/24	—	2.2/30	—
Viola nuttallii	0.6/10	—	—	—	—	—	—	—	—	—	—	—	—	—	—	+ /4	—

[1] + indicates coverage of less than 0.5%.

Table A-6.—Location, topographic position, coverage (percent), and frequency (percent) of undergrowth species in the *Abies lasiocarpa/Carex geyeri* habitat type

	Stand number				
	48	17	43	44	8
Location					
Section	18	12	34	34	12
Township	3S	8S	8S	8S	11S
Range	91W	90W	90W	90W	89W
Topographic position					
Slope (%)	—	—	45	43	40
Aspect (°)	—	—	271	269	296
Elevation (m)	2850	2804	2941	2960	2713
	Coverage[1]/Frequency				
Shrubs					
Abies lasiocarpa	4.4/20	21.0/40	13.0/34	12.0/40	9.3/18
Amelanchier alnifolia	—	—	—	—	+ /2
Lonicera involucrata	6.3/10	—	—	—	—
Pachistima myrsinites	—	—	4.1/44	5.0/46	—
Picea engelmannii	—	—	—	+ /4	—
Populus tremuloides	—	—	—	—	+ /2
Ramischia secunda	2.4/16	—	+ /4	+ /8	—
Ribes cereum	+ /4	—	—	—	—
Ribes montigenum	—	—	+ /4	+ /2	—
Rosa sp.	—	—	—	—	+ /6
Rubus idaeus	2.4/6	—	—	—	—
Rubus parviflorus	16.0/48	—	—	—	4.6/30
Symphoricarpos oreophilus	—	—	—	—	21.0/58
Vaccinium myrtillus	—	—	0.7/8	—	—
Vaccinium scoparium	—	—	0.8/16	—	+ /2
Graminoids					
Bromus ciliatus	—	3.1/28	—	—	9.8/52
Calamagrostis rubescens	—	—	—	—	0.8/6
Carex geyeri	21.0/33	29.0/82	6.9/42	5.9/24	7.9/30
Elymus glaucus	—	1.7/30	—	—	—
Melica spectabilis	—	+ /4	—	—	—
Poa nervosa	+ /2	—	—	—	+ /6
Forbs					
Achillea millefolium	—	+ /4	—	—	+ /6
Actaea rubra	—	0.6/4	—	—	—
Aquilegia caerulea	—	0.5/18	+ /4	—	—
Arnica cordifolia	—	—	7.6/52	0.5/20	3.4/28
Aster engelmannii	2.8/30	0.6/4	0.7/8	5.2/36	11.0/58
Cirsium sp.	—	4.3/26	—	—	—
Collomia linearis	—	—	—	—	+ /4
Delphinium barbeyi	—	4.1/20	—	—	0.8/8
Descurainia californica	+ /2	—	—	—	—
Epilobium angustifolium	—	—	0.7/8	—	—
Erigeron elatior	0.5/10	—	—	—	—
Erigeron speciosus	—	0.9/16	—	—	—
Fragaria sp.	—	1.0/20	—	—	2.3/30
Galium aparine	1.3/8	—	—	—	—
Galium boreale	—	1.3/32	+ /4	+ /8	3.3/56
Geranium richardsonii	+ /4	3.3/54	+ /4	—	1.2/22
Heracleum sphondylium	—	1.2/12	—	—	—
Hydrophyllum fendleri	—	3.0/24	—	—	—
Lathyrus leucanthus	—	0.7/8	4.2/32	0.9/16	17.0/70
Ligusticum porteri	2.2/8	3.6/16	4.1/20	+ /4	0.8/8
Lupinus argenteus	—	—	—	—	2.2/6
Mosses + Lichens	—	—	2.4/28	5.0/28	—
Osmorhiza depauperata	5.2/44	2.0/18	0.4/16	0.3/18	—
Osmorhiza sp.	0.6/10	—	+ /8	—	+ /6
Pedicularis racemosa	1.3/6	—	0.5/4	2.2/12	—
Polemonium caeruleum	+ /2	—	—	—	—
Potentilla gracilis	—	+ /4	—	—	—
Pseudocymopterus montanus	—	—	—	+ /8	+ /8
Ranunculus uncinatus	—	—	—	—	+ /2
Senecio serra	0.5/4	+ /4	—	—	—
Senecio wootonii	—	5.1/24	—	—	—
Smilacina racemosa	+ /4	—	—	—	—
Smilacina stellata	—	4.0/20	—	—	—
Solidago multiradiata	—	—	0.8/12	+ /6	—
Solidago spathulata	—	+ /4	+ /2	—	—
Stellaria jamesiana	—	0.6/24	—	—	—
Taraxacum sp.	—	1.7/32	—	—	+ /4
Thalictrum fendleri	1.3/8	12.0/50	—	—	—
Thlaspi montanum	—	+ /8	—	—	—
Trillium ovatum	—	—	—	—	+ /2
Valeriana occidentalis	—	11.0/62	—	—	—
Vicia americana	—	+ /6	—	—	2.0/18
Viola canadensis	+ /8	4.5/50	—	—	0.9/10
Viola nuttallii	—	+ /4	—	—	—

[1] *+ indicates coverage of less than 0.5%.*

Hoffman, George R., and Robert R. Alexander. 1983. Forest vegetation of the White River National Forest in western Colorado: A habitat type classification. USDA Forest Service Research Paper RM-249, 36 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

A vegetation classification based on concepts and methods developed by Daubenmire was used to identify eleven forest habitat types in the White River National Forest. Included were five habitat types in the *Populus tremuloides* series, two in the *Abies lasiocarpa* series, and one each in the *Pseudotsuga menziesii, Pinus edulis, Picea pungens,* and *Quercus gambelii* series. A key to identify the habitat types and the management implications associated with each is provided.

Keywords: Vegetation classification, habitat type, *Abies lasiocarpa, Picea engelmannii, Picea pungens, Pinus edulis, Pinus contorta, Populus tremuloides, Pseudotsuga menziesii, Quercus gambelii.*

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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Ten-Year Performance of Ponderosa Pine Provenances in the Great Plains of North America

Ralph A. Read

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Abstract

A cluster and discriminant analysis based on nine of the best plantations, partitioned the seed provenance populations into six geographic clusters according to their consistency of performance in the plantations.

The Northcentral Nebraska cluster of three provenances performed consistently well above the average in all plantations. These easternmost stands of ponderosa pine along the Niobrara River escarpment in Nebraska from about 101° longitude and eastward, and those in the drainage of the South Fork of the White River near Rosebud, S. Dak., are recommended for tree planting in all Great Plains states.

Acknowledgements

Much of the cooperation in establishment of the ponderosa pine provenance plantations reported in this paper was accomplished through the Regional Forest Tree Improvement Committee (NC-99) of the North Central State Agricultural Experiment Stations. In addition to all principal cooperators (appendix), the author thanks all the technicians and graduate assistants who participated in the layout, planting, maintenance, and measurement of the various plantations.

)A Forest Service
earch Paper RM-250

December 1983

Ten-Year Performance of Ponderosa Pine Provenances in the Great Plains of North America

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Ten-Year Performance of Ponderosa Pine Provenances in the Great Plains of North America

Ralph A. Read

Management Implications

Based on the 10-year results of this study, use of onderosa pine seed provenances from the Northcentral ebraska cluster (table 4) is recommended for all states the Great Plains area. More specifically, these inude the easternmost ponderosa pine stands along the iobrara River escarpment from south of Nenzel, Nebr. stward, and in the drainage of the South Fork of the hite River, near Rosebud, S. Dak.

In addition to those areas, practitioners should carelly study the data in table 3, to make use of other seed ovenances which show up as plus or double plus in antations closest to their planting sites. For example, ovenances 822 and 825 in central Montana can be commended, because they performed well above plantion means in more than 80% of the plantations (table Seed provenances which show predominantly minus mbols in table 3 should be scrupulously avoided.

Several of the best performing seed provenances reire additional comment, especially 824 and 825 in ontana, which are within an area of intensive coal rip mining. If these stands are to be kept available for ed collections, immediate action is needed. The three provenances in the Northcentral Nebraska cluster are in less danger, because they occupy private ranch lands or the Rosebud Sioux reservation lands.

These results are based on the two traits of survival and height growth. In time, other traits are very likely to be of equal importance. Traits such as needle and branching (Read and Sprackling 1981), flowering (Read and Sprackling 1983), stem form (La Farge 1975), insect susceptibility (Dix and Jennings 1982), disease susceptibility (Peterson and Read 1977), and drought resistance, all are important in the evaluation of seed provenances for use in Great Plains tree plantings. These traits should be included in future studies to provide a more comprehensive basis for population delineation by cluster analysis.

Although growth rates are probably at a maximum between 5 and 20 years, they are likely to decline after that period. Namkoong and Conkle (1976) found this to be the case in a 29-year study of elevational transect seed provenances in California. They cautioned that selection of genotypes should be delayed until the declining growth phase can be adequately observed. Therefore, it is possible that the seed provenances recommended here, which are based upon 10-year height growth, may change after 20 years of evaluation.

Introduction

The ponderosa pine complex (*Pinus ponderosa* Dougl. Laws.) in western North America (fig. 1) extends from rth latitude 23° near San Luis Potosi, Mexico to 52° in uthern British Columbia, Canada; and from west longide 99° in north-central Nebraska to 124° along the lifornia coast (Critchfield and Little 1966). Thus, these ests grow under an extremely wide range of soil oes and climatic conditions.

Three varieties are presently recognized within this mplex (Little 1979). Typical variety *ponderosa* exnds from British Columbia, west of the Continental vide, to the Snake River Plain in southern Idaho; south ong the Cascade and Coast Ranges in Washington and egon; and in the Coast and Sierra Nevada Ranges of lifornia to near San Diego.

The Rocky Mountain variety, *scopulorum* Engelm., own also as interior ponderosa pine, extends from 48° northcentral Montana, east of the Continental Divide, utheasterly into North Dakota, South Dakota, Wyong, and Nebraska. South of Wyoming this variety ocrs on both sides of the Divide in Colorado, and stward into Utah and Nevada. The name *scopulorum* sometimes extended south of the region to which it inally applied, i.e., to stands in New Mexico, Arizona, and west Texas. However, the ponderosa pine in these southern stands is distinctly different from those of the northern range *scopulorum*, especially in needle and monoterpene characteristics (Read 1980, Smith 1977).

The variety *arizonica* (Engelm.) Shaw—*Pinus arizonica* according to some authorities—extends from southwest New Mexico and southeastern Arizona southward along the Sierra Madre Occidental to near Durango, and along the Sierra Madre Oriental to near San Luis Potosi, Mexico.

Although older studies of ponderosa pine—near Pikes Peak in Colorado (1910), and Priest River, Idaho (1911)—are considered to be the earliest examples of provenance tests of forest trees in North America (Wang 1979), subsequent genetic research in ponderosa pine has concentrated mainly on the West Coast variety *ponderosa*.

Studies of genetic variation throughout the entire natural range of ponderosa pine have used various analyses to delineate varieties (Korstian 1924), geographic races (Weidman 1939), ecotypes (Wells 1964a, 1964b), regions and zones (Smith 1977), or geographic clusters (Read 1980). These studies and a study by Squillace and Silen (1962), have indicated the existence of smaller geographic groups within the populations of each variety. Because most of these

Figure 1.—Natural distribution of ponderosa pine (after Critchfield and Little 1966); location of collections in this study; and location of the two nurseries where planting stock was grown.

studies have shown that there are distinct differences in characteristics such as growth rate, seed germination rate, time of growth initiation, needle morphology, and monoterpenes, among subpopulations, it is important that such variations be recognized not only in forest management practice, but especially in seed collection practices.

The present study provides new knowledge of genetic variation in the eastern range of variety *scopulorum*, and south into New Mexico and Arizona.

The Present Study

This study was begun 20 years ago to determine the best seed provenances of ponderosa pine for use in protection plantings in the Great Plains of the United States. The first phase of the study involved assessment of seedling growth and traits in the nursery (Read 1980).

This paper continues that study by assessing the performance of the seed provenances after 10 years growth, in 17 widely dispersed field plantations. Performance data are used to revise the previous delineation of geographic clusters within the populations, and thus provide an improved basis for selecting seed provenances.

The 10-year height growth of each seed provenance, in each of 9 field plantations is used as a basis to delineate geographic clusters of seed provenances whose performance relative to other seed provenances was similar in all plantations. No other traits were measured; therefore, the results presented are based exclusively on survival and growth. Results do not address the specific interactions of survival and growth with disease or insect infestation, which might be expected to differ by seed provenance; instead, they include those effects as part of survival and growth response.

The geographic clustering resulting from the present analysis is not identical to the geographic clustering derived from the nursery seedling analysis; however, there are similarities. The seedling analysis was made on performance in a relatively uniform nursery environment, whereas field performance encompassed sites that were widely different in soil and climatic conditions. Therefore, the pertinent aspects to look for are the similarities in the general trends revealed by the two clustering analyses.

The study was begun in the early 1960's in a cooperative effort by the North Central and the Rocky Mountain Stations of the USDA Forest Service. The plan of study was prepared by scientists of the Northern Institute of Forest Genetics.[2] The objectives were:

1. to acquire knowledge of the extent and distribution of genetic variation in natural stands of the eastern range of ponderosa pine;
2. to find the best adapted seed provenances for planting in different parts of the Great Plains; and
3. to provide a broad range of genetic materials at convenient sites for the selection and breeding of improved trees, and for long-term studies of drought, disease, and insect resistance.

The nursery seedling evaluation phase of the study and its part in meeting the first objective has been reported by Read (1980). A complete description of the materials used in this study is contained in that publication. Briefly, seeds were collected from 1962 through 1964, from 10 to 15 trees in each population, sampled at each of 79 locations (fig. 1). Seven locations were in the var. *ponderosa* region, generally west of the Continental Divide, and 72 locations were in the var. *scopulorum* region of the eastern range. Seedlings for the nursery study and planting stock for the field study were grown at the Forest Service Bessey Nursery in Nebraska, and at North Dakota's Towner Nursery from 1965 through 1968 (fig. 1).

Field plantations were established from 1968 through 1970. Preliminary data and height growth performance have been published as follows:

- Browsing preferences by jackrabbits in Nebraska (Read 1971).
- Variation in resin canal numbers in Kansas (Deneke and Funsch 1972).
- 5-year height in Minnesota (Tauer, Mohn, and Cromell 1974).
- 5-year height in Black Hills, South Dakota (Van Deusen 1974).
- 6-year height in Kansas (Deneke and Read 1975).
- 4- and 6-year height in Pennsylvania (Davidson 1977).
- Western gall rust in Nebraska (Peterson and Read 1977).
- 9-year height in Oklahoma (Tauer and Gardner 1978).
- 10-year height in South Dakota (Baer and Collins 1979).
- 10-year height in North Dakota (Van Deusen 1980).
- Hail damage variation in Nebraska (Read and Sprackling 1981).
- 10-year height in Minnesota (Radsliff et al. 1981).
- Western pine tipmoth in Nebraska (Dix and Jennings 1982).
- Flowering at 13 years in Nebraska (Read and Sprackling 1983).

[2] *Nienstaedt, Hans, and David H. Dawson. 1964. Study workplan for ponderosa pine for the Great Plains region (a study of the adaptability of provenances from the eastern portions of its native range). Lake States Forest Experiment Station (now North Central), USDA Forest Service, 94 p. (On file Rocky Mountain Station Laboratory, Lincoln, Nebr.).*

Materials and Methods

Field plantations of the seed provenance progenies were established at various locations (fig. 2), mostly in the Great Plains, from 1968 through 1970.[3] Twenty-eight plantations were initially established. Ten of them were omitted because they had very low survival or no data available. A 4-tree-plot plantation at Hastings, Nebr. was omitted, because a 25-tree-plot plantation at that location provided adequate representation.

The basic design for field testing was to be randomized blocks with 4-tree plots and 15 replications. That design was followed in seven plantations. However, for various reasons, some cooperators used 6- or 10-tree plots, while others divided their materials, in order to plant fewer replicates at several locations. Three plantations contained 50 or fewer of the 79 seed provenances; the Plattsmouth, Nebr. and Norman, Okla. plantations were designed that way. The Philipsburg, Pa. plantation contained only 49 seed provenances because of planting stock shortage.

Data on location and layout design for the 17 plantations in this paper are shown in table 1. Methods of site preparation and maintenance after planting were left to the judgment of each cooperator. In most plantations, land was prepared by plowing, disking, rotovating, or harrowing. In a few plantations on light sandy soils, the sites were not disturbed, except by herbicide applied to control grass, weeds, or brush. Maintenance ranged from harrowing, over-the-row cultivation, and herbicide application to mowing. Only one plantation received no maintenance. Control of gophers, rabbits, or porcupines was necessary in several plantations.

Spacing of trees within each layout was left to the discretion of each cooperator. It ranged from 6 x 6 feet in the Michigan and Pennsylvania plantations to 6 x 8, 6 x 12, 8 x 8, 8 x 12, and 8 x 13 feet to 12 x 12 feet in Oklahoma.

Planting stock distribution from the two nurseries was as follows: Saskatchewan, North Dakota, Minnesota, South Dakota, and Michigan received stock grown at Towner, N. Dak.; Alberta, Nebraska, Kansas, Oklahoma, Missouri and Pennsylvania received stock grown at Bessey Nursery, Nebraska.

In the analysis of data, the primary objective was to identify superior seed provenances across the range of plantation locations. As the first step, the 10-year height data of each plantation were subjected to standard analysis of variance and unequal sample size multiple range tests. These analyses indicated the presence of significant variation among seed provenances for each plantation. However, the replication of each seed provenance was sufficient to statistically detect only differences between extremes (i.e., the tallest from the shortest provenances). Therefore, because the results were not particularly informative, they are not reported.

ISODATA cluster analysis (Ball and Hall 1965, 1966) was then used to group seed provenances based on the

[3] *Read, Ralph A., and Paul E. Slabaugh. Establishment Report for Ponderosa Pine Provenances for the Great Plains. Timber Management Research Studies: 1501.13, Lincoln, Nebr.; 1502.4, Bottineau, N. Dak. 1971, 101 p. (mimeographed).*

Figure 2.—Location of the seventeen field plantations. Circled locations are those used in ISODATA analysis. Numbers in ( ) are used in Tables 1 and 2.

Table 1.—Location and establishment data for the seventeen plantations, grouped by Northern, Central, and Southern and Eastern locations

State or Province	No. of Plantation location	°Lat.	°Long.	Elevation (ft)	Elevation (m)	Seed provenances	Trees per plot	Repli-cations	Trees per provenance
ALB	Drumheller	51.3	112.6	2,660	811	63	10	3	30
SASK	Indianhead	50.4	103.6	1,800	549	70	4	15	60
ND	Towner	48.4	100.4	1,500	457	79	4	15	60
MN (1)	Grand Rapids	47.2	93.5	1,300	396	70	4	3	12
MN (2)	Morris	45.6	95.9	1,100	335	72	4	6	24
MN (3)	Lamberton	44.2	95.2	1,000	305	72	4	9	36
SD	Watertown	44.9	97.1	1,740	530	73	4	8	32
NE (1)	Alliance	42.1	102.9	4,000	1219	79	4	15	60
NE (2)	Halsey	41.9	100.4	2,900	884	79	4	15	60
NE (3)	Hastings	40.6	98.3	1,900	579	79	25	4	100
NE (4)	Plattsmouth	41.0	95.9	1,100	335	50	10	6	60
KS	Milford	39.0	96.9	1,000	305	77	4	15	60
OK	Norman	35.1	97.5	1,100	335	40	4	15	60
MO (1)	Mt. Vernon	37.1	93.9	1,200	366	78	4	10	40
MO (2)	Columbia	38.9	92.2	700	213	78	4	10	40
MI	Kellog	42.4	85.4	800	244	75	6	5	30
PA	Philipsburg	41.0	78.2	1,600	488	49	10	6	60

imilarity in relative height growth across the range of lantation locations.

Because performance in each plantation was indeendent of all other plantations, the average height rowth of each seed provenance in the different plantaons was used as an independent trait. Use of the luster analysis makes it possible to ascertain how conistently similar, or not, the seed provenances or lusters behave in all plantations.

To perform the cluster analysis using all provenances nd all plantations, it would have been necessary to stimate 160 missing cells in the matrix of 79 seed provnances and 17 plantations (about 12% of total). Sixty-ght missing cells were in two of the plantations at lattsmouth, Nebr. and Norman, Okla., which were esigned that way. Shortage of planting stock of Oregon, /ashington, Idaho, and four Bitterroot, Montana seed rovenances, which were not planted in approximately lf the plantations, was responsible for the remaining issing values.

Therefore, to include the maximum number of provnances (78) with a minimum insertion of estimated lues, nine plantations were chosen (fig. 2) for analysis: askatchewan, North Dakota, three Nebraska locations, ansas, two Missouri locations, and Michigan. Provenance 753 was omitted in analysis because it was anted in only five plantations; however, it is included the data tables along with other provenances in the rge cluster which covers most of central and eastern ontana. Excluding that provenance, only 12 missing ot values had to be estimated by a randomized block chnique (John 1971).

Discriminant analysis was used to assess the degree separation among the clusters of seed provenances. dividual provenances, possibly misclassified by the uster analysis, were also identified and were placed in e indicated cluster.

Average tree heights for each seed provenance were nverted to percentages of each plantation's mean. his technique is commonly used to compare relative ights of seed provenances in widely dispersed plantons, where different environments have produced rge differences in mean growth of plantations. The location of these percentages into broad performance asses then facilities comparison among plantations to ow consistency, or lack of it, in how seed provenances rform across all plantations.

Results and Discussion

The geographic clusters delineated in the cluster alysis of 9 plantations and 78 seed provenances were early distinct, with few exceptions. Discriminant alysis, which applied unequal weighting to the plantons according to ability to distinguish among the usters (cluster analysis applies equal weighting), entified only two provenances possibly misclassified. ovenance 727, first placed in the Foothills-Black Hills uster, was considered more likely to belong in the rthern High Plains cluster. Provenance 867, first aced in the Southern cluster, was judged to be part of the Northwest cluster. Apart from these two misfits, the separation among clusters was good with posterior probabilities of generally 0.8 or larger that cluster members were properly classified. Results are summarized in figure 3 and table 2.

The seven provenances west of the Continental Divide in the Northwest formed a distinct cluster. This agrees with results of the cluster analysis of seedling traits which described this group as var. *ponderosa* (Read 1980). All provenances in this cluster were generally poor performers in the Great Plains plantations, showing low survivals and slow growth. The only exceptions were in the Missouri and Michigan plantations, where several provenances, including Idaho and Washington, appeared sufficiently adapted to perform well.

The five Southern seed provenances formed another distinct cluster in central and southern New Mexico and Arizona. In the seedling analysis (Read 1980), this cluster included three provenances in southern Colorado and northern New Mexico (765, 862, 863). The failure and poor performance of these five Southern provenances in all northern plantations, where they were not adapted, accounts for the difference in clustering in this southern range. Southern provenances survived reasonably well in Nebraska and southward plantations, but they grew well only in the Plattsmouth, Nebr., Oklahoma, and Missouri plantations.

The Central Rocky Mountain cluster, though smaller than that obtained in the seedling analysis (Read 1980), is nevertheless indicative of a group of seed provenances of low growth potential for use in the Great Plains. Practically all 10 provenances in this cluster, although showing reasonably good survival, were below average performance in all plantations.

In contrast to the three previously described clusters, the Northern High Plains cluster of 25 seed provenances in central and eastern Montana, and extending southeastward to the east of the Black Hills into northwestern Nebraska, contains a number of high performance, and only a few low performance seed provenances. In all 17 plantations, the average survival and performance of the 25 seed provenances in this cluster was consistently above the plantation means.

The cluster of three provenances in Northcentral Nebraska and adjacent southcentral South Dakota was distinct. These provenances survived and grew in height consistently better than any other cluster in practically all plantations. Except for one isolated Nebraska population (856), these seed provenances represent the extreme eastern range of the species.

The cluster of 29 provenances designated as Foothills-Black Hills appeared to be intermediate in growth, between the Northern High Plains and the Central Rocky Mountain clusters, at least in the central, southern, and eastern plantations. Seed provenance locations in this cluster ranged from northcentral Montana to northern New Mexico; and with the exception of three provenances in northern Montana, one in North Dakota, and one in central Nebraska, all formed a fairly cohesive cluster. None of the seed provenances were consistently high performers; but some northern Montana prove-

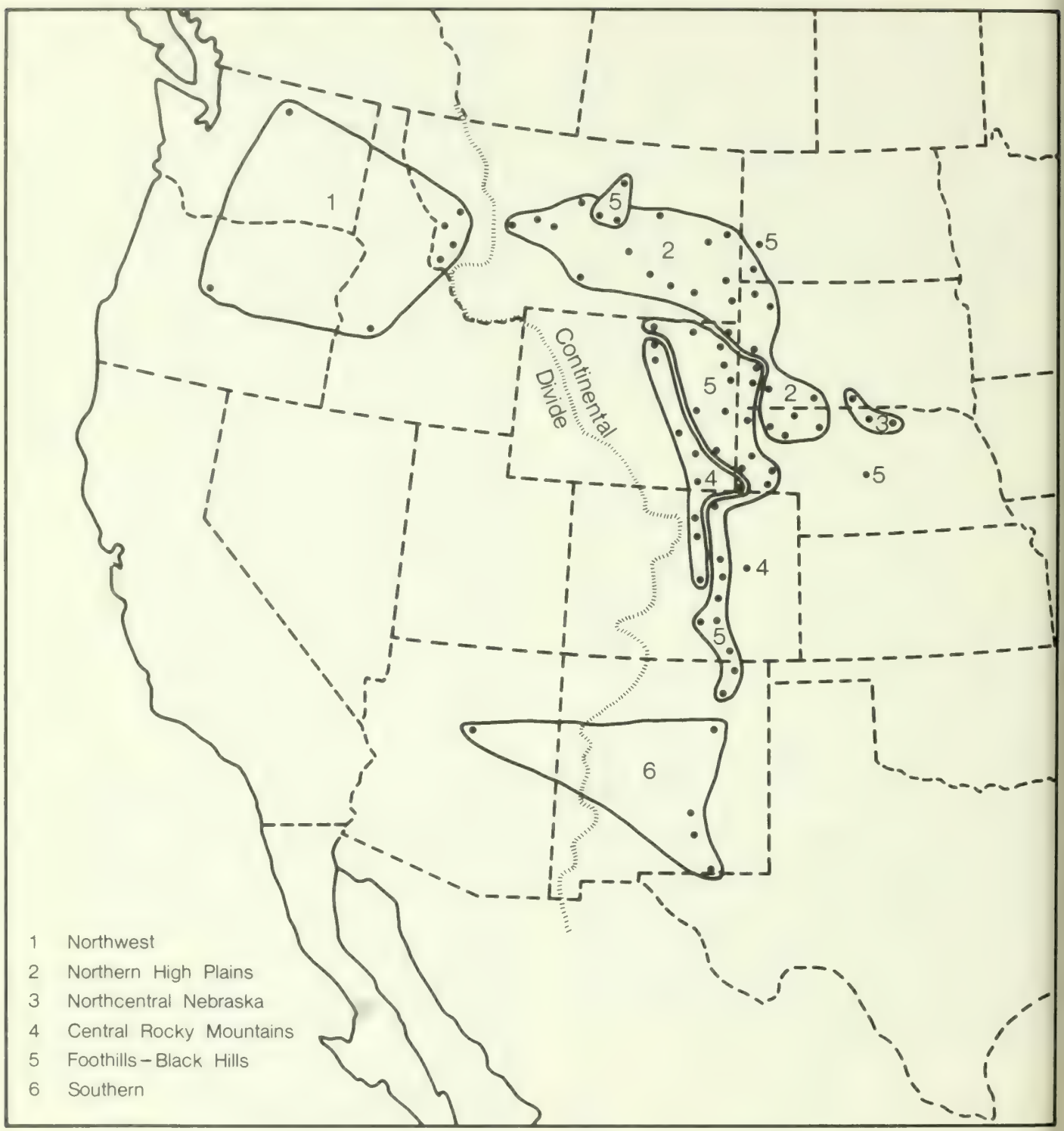

Figure 3.—Delineation of population clusters as derived from the cluster-discriminate analysis.

nances were excellent in Alberta, and some Black Hills provenances were top performers in the western Nebraska plantation.

Average percent survival data for all 78 seed provenances and plantations (except Michigan) showed a similar, but not identical, clustering as the growth data. The data reveal that provenances in the Northcentral Nebraska and the Northern High Plains clusters generally survived the best. The Central Rocky Mountains and the Foothills-Black Hills clusters showed slightly poorer survival. Provenances in the Northwest and the Southern clusters generally exhibited poor survival. Some variation in this general trend was present for particular plantations.

Table 2.—Mean survival, height, and percent of plantation $\bar{x}$ of the six clusters by plantations[1]

Cluster	No. of Provenances		Northern Plantations							Central Plantations					Southern and Eastern Plantations				
			ALB	SASK	ND	MN (1)	MN (2)	MN (3)	SD	NE (1)	NE (2)	NE (3)	NE (4)	KS	OK	MO (1)	MO (2)	MI	PA
Northwest	7	% surv.	65	9	12	54	42	26	73	31	26	64	96	54	66	91	92	–	np
		Mean Ht.	2.5	3.8	1.6	5.2	5.6	3.9	5.6	4.4	3.3	7.8	13.0	3.3	7.0	8.2	10.0	13.1	
		% PL. $\bar{X}$	66	68	70	87	83	59	76	66	80	91	101	79	98	95	107	111	
Northern High Plains	25	% surv.	75	60	61	76	69	58	94	80	48	99	99	90	88	99	93	–	65
		Mean Ht.	4.2	6.0	2.4	6.4	7.4	7.2	8.3	7.0	4.6	9.2	13.7	4.6	7.3	9.0	10.0	12.4	5.7
		% PL. $\bar{X}$	110	108	105	107	110	109	112	104	112	107	107	110	102	105	107	105	105
North-Central Nebraska	3	% surv.	77	68	72	75	81	65	95	79	42	99	100	88	91	99	96	–	64
		Mean Ht.	4.4	7.6	3.3	6.4	8.4	8.1	9.6	7.7	5.5	11.3	14.9	7.1	10.5	10.7	10.7	13.8	7.4
		% PL. $\bar{X}$	115	136	145	107	125	123	130	115	133	132	116	170	147	124	114	117	137
Central Rocky Mountains	10	% surv.	68	34	47	71	68	49	82	87	41	99	98	85	74	96	85	–	69
		Mean Ht.	3.6	4.2	2.0	5.2	5.5	5.7	6.0	6.2	3.3	7.2	11.0	3.4	5.4	6.9	7.4	10.0	4.7
		% PL. $\bar{X}$	94	75	88	87	82	86	81	92	80	84	86	81	76	80	79	85	87
Foothills-Black Hills	29	% surv.	63	42	44	61	62	49	84	85	38	98	98	87	77	98	91	–	56
		Mean Ht.	3.6	5.0	2.0	5.8	6.4	6.3	6.9	6.8	3.9	8.4	12.5	4.0	6.7	8.5	9.1	11.6	5.3
		% PL. $\bar{X}$	94	90	88	97	95	96	93	101	95	98	97	96	94	99	97	98	98
Southern	5	% surv.	0	0	0	0	0	14	17	64	6	77	91	64	75	86	69	–	np
		Mean Ht.	0	0	0	0	0	4.7	2.2	6.3	1.1	7.8	13.1	3.6	7.7	10.4	10.2	11.9	
		% PL. $\bar{X}$	0	0	0	0	0	71	30	94	27	91	102	86	108	121	109	101	
Provenances	79		63	70	79	70	72	72	73	79	79	79	50	77	40	78	78	75	49
Plantation:																			
Mean survival (%)			66	44	45	66	61	50	84	77	37	94	98	83	80	96	89	–	61
Mean height (feet)			3.8	5.6	2.3	6.0	6.7	6.6	7.4	6.7	4.1	8.6	12.8	4.2	7.1	8.6	9.4	11.8	5.4
Cluster basis				*	*					*	*	*		*		*	*	*	

[1]*Explanation: np = none planted; 0 = planted, zero survived; * = plantations used in ISODATA cluster analysis (see circled locations in Fig. 2).*

The consistent performance of seed provenances in the Northcentral Nebraska and the Northern High Plains clusters is very remarkable, in that this response extends across all or nearly all plantations. Consider the range of climatic variables from Oklahoma to Alberta (over 16 degrees latitude), and from Alberta to Michigan and Pennsylvania (over 34° longitude). Mean annual temperature ranges from 60° F in Oklahoma to approximately 30° F in Alberta, and mean annual precipitation from 32 inches to a little more than 10 inches. The growing season averages 224 days in Oklahoma but less than 100 days in Alberta.

Under such a large range of environmental conditions, the evidence is strong that the northcentral Nebraska and southcentral South Dakota provenances, and some in central Montana, contain genes endowing them with a much broader range of site tolerance for the Great Plains, than for example the seed provenances in the Central Rocky Mountain cluster.

Mean heights of each seed provenance by cluster and plantation are shown in table 3A (Northern), table 3B (Central), and table 3C (Southern and Eastern) plantations. Included in these tables are symbols which denote a subjective characterization of height growth in each plantation. These are intended only to show a comparison of similarities and differences across plantations and do not imply statistical significance. The mean heights of each provenance in a plantation, relative to the plantation mean, are divided into five broad percentage groups, as follows:

+ +	heights greater than 130% of plantation mean
+	heights ranging from 111% to 130%
no symbol	heights ranging from 90% to 110% about the mean
–	heights ranging from 70% to 89%
– –	heights less than 70% of plantation mean

In the seven northern plantations (table 3A), the Southern cluster provenances either failed or grew very slowly. Provenances of the Central Rocky Mountains, most of the provenances in the Foothills-Black Hills cluster, and all Northwest provenances showed poor performance. The best provenances in these northern plantations were from the Northern High Plains and Northcentral Nebraska clusters. Central and eastern Montana provenances 816, 812, 821, 822, 811, 824, 825, 727, and 826 all showed better than 110% performance in more than half of these plantations. One provenance 837 from the eastern side of Black Hills performed well in four of the seven plantations. Northcentral Nebraska provenances 720 and 721, and southcentral South Dakota 757 performed exceptionally well in nearly all plantations.

In five central Great Plains plantations (table 3B), growth performance was similar but showed a slightly different pattern than in the northern plantations. The southern provenances from New Mexico, Arizona, and southern Colorado survived in most plantings, in contrast to performance in northern plantations; but growth rate was only average or below. All Central Rocky Mountain and Northwest provenances were poor performers. As in the northern plantations, certain provenances from central and eastern Montana were consistently taller than plantation means. In addition, some Black Hills provenances and several from western Nebraska (833 through 855) showed up as good performers. The Northcentral Nebraska provenances 720 and 721, and South Dakota 757 performed exceptionally well, as in the northern plantations.

In the three southern and two eastern plantations (table 3C), the three Northcentral Nebraska provenances again show up as the fast-growers. Central and eastern Montana provenances also grew well in most plantations. The only plantations in which Southern provenances appear to be well adapted were Oklahoma and Missouri. However, the three southernmost provenances of the Foothills-Black Hills Cluster, 765, 862, and 863, appeared to be well-adapted in Missouri and in Pennsylvania. The Washington and Idaho provenances appeared as fast-growers in central Missouri and in Michigan. All Central Rocky Mountain provenances performed poorly in all five of these plantations.

Based on the 10-year results of this study, use of ponderosa pine seed provenances from the Northcentral Nebraska cluster (table 4) is recommended for all states in the Great Plains area. More specifically, these include the easternmost ponderosa pine stands along the Niobrara River escarpment from south of Nenzel, Nebr. eastward, and in the drainage of the South Fork of the White River, near Rosebud, S. Dak.

In addition to those areas, practitioners should carefully study the data in table 3, to make use of other seed provenances which show up as plus or double plus in plantations closest to their planting sites. For example, provenances 822 and 825 in central Montana can be recommended, because they performed well above plantation means in more than 80% of the plantations (table 4). Seed provenances which show predominantly minus symbols in table 3 should be scrupulously avoided.

Table 3A.—Average tree heights (in feet) for each seed provenance in Northern plantations, and symbols to show percentage-of-plantation mean classes[1]

Seed Provenance Location & No.		Drumheller ALB	Indianhead SASK	Towner ND	Grand Rapids MN	Morris MN	Lamberton MN	Watertown SD
Northwest								
OR	865	np	3.4 --	1.3 --	4.4 –	np	np	5.6 –
WA	866	np	4.5 –	1.4 --	5.9	6.3	5.0 –	7.2
ID	867	np	0 --	0 --	np	4.5 --	3.3 --	3.8 --
MT	817	np	np	2.5	np	np	np	np
MT	818	np	np	1.8 –	np	np	np	np
MT	819	2.5 --	np	1.6 –	np	np	np	np
MT	820	np	np	1.7 –	np	np	np	np
Northern High Plains								
MT	816	4.3 +	6.1	2.8 +	6.6 +	7.9 +	7.1	8.7 +
MT	754	3.4 –	5.6	2.7 +	5.7	5.8 –	6.7	7.7
MT	753	np	np	2.2	np	np	np	7.5
MT	812	4.3 +	5.8	2.4	6.8 +	7.5 +	7.0	8.3 +
MT	821	np	6.5 +	2.4	7.7 +	8.8 + +	7.9 +	8.1
MT	822	4.5 +	7.6 + +	2.5	7.2 +	8.2 +	8.8 + +	9.0 +
MT	811	4.3 +	6.7 +	3.0 + +	8.5 + +	6.6	6.9	7.9
MT	823	2.8 –	5.9	2.6 +	6.4	7.2	7.3 +	8.4 +
MT	824	5.3 + +	5.7	2.6 +	6.6 +	8.4 +	6.7	8.3 +
MT	825	4.8 +	6.6 +	2.8 +	7.5 +	6.7	7.6 +	8.9 +
MT	727	3.9	6.7 +	2.8 +	5.2 –	7.7 +	8.6 +	8.3 +
MT	826	np	7.1 +	2.2	7.9 + +	8.5 +	8.3 +	8.7 +
MT	827	4.1	5.4	2.4	6.1	7.2	7.5 +	8.3 +
MT	828	np	6.2 +	2.4	6.4	6.0 –	7.2	8.4 +
ND	701	4.6 +	5.4	2.1	5.1 –	5.9 –	6.9	8.7 +
SD	703	4.2	6.6 +	2.6 +	5.6	8.5 +	7.1	7.8
SD	704	4.1	5.8	2.4	6.1	7.8 +	6.3	8.0
WY	833	5.0 + +	6.2 +	2.2	6.2	7.2	7.2	7.5
SD	837	4.7 +	5.9	2.3	7.2 +	9.0 + +	6.7	8.7 +
SD	840	5.2 + +	5.6	1.9 –	5.5	5.9 –	7.4 +	8.6 +
NE	722	3.6	5.8	2.7 +	5.1 –	7.1	6.3	8.5 +
NE	852	3.9	5.2	2.1	5.3 –	6.9	6.7	7.5
NE	853	3.7	4.6 –	2.4	6.3	7.8 +	7.2	8.7 +
SD	854	3.5	5.2	1.9 –	5.8	5.4 –	5.8 –	8.6 +
NE	855	4.3 +	5.0	2.4	6.2	6.2	7.5 +	9.2 +

Table 3A.—Average tree heights (in feet) for each seed provenance in Northern plantations, and symbols to show percentage-of-plantation mean classes[1]—Continued

Seed Provenance Location & No.		Drumheller ALB	Indianhead SASK	Towner ND	Grand Rapids MN	Morris MN	Lamberton MN	Watertown SD
Northcentral Nebraska								
SD	757	4.5 +	7.5 + +	3.2 + +	6.8 +	7.4	7.9 +	9.5 +
NE	721	3.7	7.8 + +	3.4 + +	6.7 +	8.8 + +	8.3 +	9.9 + +
NE	720	4.8 +	7.6 + +	3.2 + +	5.9	8.8 + +	8.1 +	9.4 +
Central Rocky Mountains								
WY	830	2.9 –	4.7 –	2.1	4.6 –	6.5	5.5 –	6.0 –
WY	831	4.6 +	4.6 –	1.8 –	5.7	5.0 –	5.4 –	6.2 –
WY	848	3.8	4.4 –	1.5 --	5.4	5.4 –	5.6 –	6.5 –
WY	847	4.4 +	np	2.3	5.2 –	4.8 –	5.5 –	5.4 –
WY	857	3.1 –	4.2 –	1.2 --	5.3 –	5.6 –	5.9	5.9 –
NE	844	3.0 –	np	1.6 –	5.0 –	4.1 --	6.3	5.7 –
CO	760	3.1 –	4.2 –	1.7 –	4.9 –	4.8 –	5.7 –	5.5 –
CO	761	3.9	2.9 --	2.2	5.4	6.0 –	5.5 –	5.7 –
CO	762	3.0 –	4.2 –	1.9 –	3.9 --	6.5	5.4 –	5.8 –
CO	763	3.8	4.4 –	2.6 +	6.1	5.8 –	6.1	7.5
Foothills-Black Hills								
MT	813	4.4 +	6.0	2.3	7.2 +	6.4	7.3 +	6.7
MT	815	4.5 +	5.7	2.6 +	6.9 +	6.8	5.7 –	8.0
MT	814	3.6	6.0	2.5	6.4	6.2	6.7	7.1
ND	702	4.7 +	4.5 –	2.2	5.4	7.0	5.8 –	7.8
WY	829	4.1	5.0	2.1	6.1	6.7	4.8 –	6.4 –
WY	832	3.9	4.3 –	1.9 –	5.9	6.2	6.4	7.4
WY	834	5.2 + +	5.7	2.4	7.0 +	6.1	6.8	8.4 +
WY	835	3.7	5.4	2.0 –	5.6	5.7 –	6.4	8.1
WY	836	3.9	5.0	2.1	6.3	6.1	7.0	8.4 +
SD	838	4.3 +	4.5 –	2.3	5.7	6.3	6.5	8.1
SD	839	3.7	5.2	1.9 –	6.4	7.9 +	6.7	8.1
WY	849	2.2 --	5.1	1.7 –	4.7 –	5.9 –	6.1	6.6 –
WY	850	3.2 –	4.7 –	1.9 –	5.5	5.5 –	5.3 –	6.2 –
NE	851	3.2 –	4.9 –	1.9 –	5.4	5.9 –	7.2	7.1
WY	846	4.0	6.0	1.5 --	5.5	7.4	8.2 +	6.3 –
NE	723	3.0 –	4.7 –	2.5	5.0 –	7.3	6.7	7.3
NE	845	3.9	np	1.9 –	5.4	5.7 –	4.0 --	6.7
NE	759	2.5 --	4.4 –	2.0 –	7.7 +	7.2	7.2	7.6
NE	758	2.9 –	4.2 –	2.1	5.3 –	6.5	5.8 –	7.6
NE	856	3.2 –	3.9 –	2.5	6.0	6.7	5.1 –	8.1
CO	858	2.1 --	4.0 –	1.7 –	5.2 –	5.3 –	5.6 –	5.2 –
CO	859	2.3 --	4.2 –	1.4 --	6.1	5.9 –	4.6 –	6.1 –
CO	724	2.9 –	3.9 –	1.8 –	4.7 –	5.0 –	5.7 –	6.9
CO	860	2.8 –	3.5 --	1.1 --	5.7	4.6 --	6.6	5.6 –
CO	861	2.5 --	4.0 –	1.5 --	4.5 –	5.9 –	4.4 --	4.8 --
CO	764	4.3 +	3.4 --	1.6 –	5.2 –	5.0 –	5.1 –	5.4 –
CO	765	2.4 --	np	1.1 --	0 --	6.6	6.5	5.0 --
NM	862	2.1 --	3.4 --	0 --	0 --	np	np	4.0 --
NM	863	np	4.3 –	0 --	0 --	0 --	4.2 --	2.0 --
Southern								
NM	864	np	0 --	0 --	0 --	0 --	5.6 –	np
NM	766	np	0 --	0 --	0 --	0 --	3.0 --	2.9 --
NM	767	np	0 --	0 --	np	0 --	4.8 –	0 --
NM	768	np	0 --	0 --	np	0 --	4.4 --	2.5 --
AZ	869	np	0 --	0 --	np	0 --	5.6 –	np
Plantation mean height		3.81	5.57	2.28	5.97	6.72	6.59	7.40
Total sources		63	70	79	70	72	72	73

[1]*Explanation: np = none planted; 0 = planted, zero survived.*
Symbols for percentage-of-plantation mean classes:
+ + greater than 130%
+ 111% to 130%
mean) 90% to 110%
– 70% to 89%
-- less than 70%

Table 3B.—Average tree heights (in feet) for each seed provenance in Central plantations, and symbols to show percentage-of-plantation mean classes[1]

Seed Provenance Location & No.		Alliance NE	Halsey NE	Hastings NE	Plattsmouth NE	Milford KS
Northwest						
OR	865	5.0 –	3.9	7.8	np	np
WA	866	4.6 --	2.7 --	7.2 –	np	3.8
ID	867	4.2 --	2.8 --	8.7	np	2.8 – –
MT	817	4.1 --	3.0 –	7.3 –	np	4.0
MT	818	4.9 –	3.2 –	6.9 –	np	2.7 – –
MT	819	4.3 --	3.9	8.2	13.5	3.0 –
MT	820	4.1 --	3.1 –	7.9	12.5	3.5 –
Northern High Plains						
MT	816	6.4	5.2 +	9.5 +	13.8	4.7 +
MT	754	6.5	4.9 +	9.0	np	5.2 +
MT	753	5.0 –	4.2	8.3	np	np
MT	812	7.4	4.1	8.6	np	4.6
MT	821	6.5	4.1	9.4	np	4.5
MT	822	7.4	4.8 +	10.3 +	15.2 +	4.9 +
MT	811	7.3	4.5	10.2 +	14.3 +	4.7 +
MT	823	6.8	5.1 +	9.3	np	4.9 +
MT	824	7.0	4.6 +	9.2	14.1	4.4
MT	825	7.9 +	4.8 +	10.0 +	np	5.1 +
MT	727	7.2	4.3	8.1	np	3.6 –
MT	826	6.3	3.8	8.5	13.5	4.0
MT	827	7.1	4.7 +	9.4	13.9	4.7 +
MT	828	7.7 +	4.8 +	8.4	np	4.7 +
ND	701	7.5 +	4.0	8.9	np	4.0
SD	703	7.1	4.4	9.2	np	4.1
SD	704	6.7	4.2	8.8	13.1	4.4
WY	833	7.1	4.2	9.8 +	13.4	4.1
SD	837	7.3	4.3	9.7 +	12.6	4.4
SD	840	7.0	5.2 +	9.1	13.6	4.4
NE	722	7.1	5.0 +	8.8	np	4.6
NE	852	7.2	4.7 +	9.9 +	13.3	4.6
NE	853	7.0	5.1 +	8.9	13.9	5.1 +
SD	854	6.7	4.3	9.1	13.6	4.7 +
NE	855	7.9 +	5.0 +	9.3	np	5.1 +
Northcentral Nebraska						
SD	757	7.9 +	5.8 + +	11.0 +	np	6.4 + +
NE	721	7.8 +	4.3	11.0 +	14.8 +	6.9 + +
NE	720	7.4	5.6 + +	11.8 + +	14.9 +	8.1 + +
Central Rocky Mountains						
WY	830	6.0 –	3.2 –	7.2 –	np	3.4 –
WY	831	6.0 –	3.5 –	7.5 –	11.2 –	4.2
WY	848	5.7 –	3.1 –	7.3 –	11.1 –	3.0 –
WY	847	6.9	2.8 --	8.0	np	3.1 –
WY	857	5.9 –	2.6 --	7.1 –	10.3 –	3.6 –
NE	844	6.5	3.0 –	7.1 –	np	3.2 –
CO	760	5.3 –	3.2 –	6.6 –	9.5 –	3.1 –
CO	761	6.6	3.3 –	7.1 –	np	3.2 –
CO	762	6.2	4.5	7.2 –	12.3	3.2 –
CO	763	7.0	3.6 –	7.4 –	11.5	3.6 –

Table 3B.—Average tree heights (in feet) for each seed provenance in Central plantations, and symbols to show percentage-of-plantation mean classes[1]—Continued

Seed Provenance Location & No.		Alliance NE	Halsey NE	Hastings NE	Plattsmouth NE	Milford KS
Foothills-Black Hills						
MT	813	6.7	3.3 –	8.0	11.6	4.0
MT	815	7.4	3.8	8.3	13.1	3.4 –
MT	814	6.8	3.6 –	8.9	np	4.0
ND	702	6.7	4.1	8.5	13.0	3.8
WY	829	6.2	3.5 –	8.3	12.0	4.3
WY	832	6.8	4.3	9.5 +	13.6	4.8 +
WY	834	8.4 +	3.7	8.2	12.1	4.0
WY	835	7.5 +	3.8	9.0	12.9	4.0
WY	836	7.7 +	4.1	8.6	np	3.5 –
SD	838	7.1	4.4	7.7	12.1	4.0
SD	839	7.2	4.4	8.6	np	3.8
WY	849	6.5	3.1 –	8.8	12.8	3.7 –
WY	850	7.2	4.1	7.7	np	4.3
NE	851	6.7	3.8	8.4	13.0	4.1
WY	846	7.3	4.1	8.0	12.6	4.8 +
NE	723	6.5	4.4	9.0	13.0	4.5
NE	845	5.8 –	4.0	8.4	11.7	3.4 –
NE	759	7.3	4.5	9.1	np	4.3
NE	758	7.0	4.7 +	7.7	12.9	3.7 –
NE	856	7.0	4.3	8.4	12.6	5.0 +
CO	858	5.9 –	2.9 –	8.1	np	3.7 –
CO	859	6.9	4.2	8.1	11.7	3.2 –
CO	724	6.4	3.8	8.1	np	3.9
CO	860	6.2	3.8	7.4 –	11.3 –	3.5 –
CO	861	5.4 –	3.2 –	7.8	12.1	3.8
CO	764	6.6	3.9	9.3	12.6	4.4
CO	765	6.8	3.9	8.6	13.7	4.7 +
NM	862	6.3	4.2	7.3 –	11.7	3.9
NM	863	6.2	3.6 –	8.5	13.3	3.5 –
Southern						
NM	864	5.5 –	2.6 --	7.2 –	12.3	3.9
NM	766	6.5	0 --	8.2	13.0	2.9 --
NM	767	6.4	0 --	8.1	13.3	3.2 –
NM	768	6.9	0 --	7.7	13.6	3.8
AZ	869	6.0 –	0 --	7.8	13.3	3.7 –
Plantation mean height		6.71	4.12	8.56	12.83	4.18
Total sources		79	79	79	50	77

[1]*Explanation: np = none planted; 0 = planted, zero survived.*
Symbols for percentage-of-plantation mean classes:

+ + *greater than 130%*
+ *111% to 130%*
(mean) 90% to 110%
– *70% to 89%*
-- *less than 70%*

Table 3C.—Average tree heights (in feet) for each seed provenance in Southern and Eastern plantations, and symbols to show percentage-of-plantation mean classes[1]

Seed Provenance Location & No.		Norman OK	Mt. Vernon MO	Columbia MO	Kellog MI	Philipsburg PA
Northwest						
OR	865	np	8.0	9.4	13.0	np
WA	866	6.8	7.8	10.8 +	13.6 +	np
ID	867	np	8.5	10.1	13.7 +	np
MT	817	np	7.6 –	9.2	11.9	np
MT	818	np	8.7	10.5 +	13.2 +	np
MT	819	np	8.3	9.8	13.2 +	np
MT	820	7.4	8.6	10.0	13.3 +	np
Northern High Plains						
MT	816	6.8	8.0	10.6 +	13.9 +	np
MT	754	6.8	7.6 –	9.6	12.3	4.5 –
MT	753	np	np	np	np	np
MT	812	np	9.0	10.2	12.8	5.6
MT	821	7.4	9.1	9.6	11.8	np
MT	822	np	9.8 +	11.6 +	13.4 +	5.6
MT	811	8.0 +	9.0	10.2	13.4 +	np
MT	823	np	9.4	10.3	12.5	6.4 +
MT	824	np	9.6 +	9.9	13.5 +	6.4 +
MT	825	8.2 +	9.1	11.1 +	13.4 +	6.8 +
MT	727	np	8.5	8.6	11.1	np
MT	826	6.5	8.6	9.1	11.8	np
MT	827	np	9.3	10.6 +	12.1	5.6
MT	828	np	9.1	10.1	13.4 +	np
ND	701	np	9.1	9.8	11.9	6.2 +
SD	703	np	7.8	9.0	12.3	5.1
SD	704	7.1	9.0	9.6	11.7	6.5 +
WY	833	np	8.6	10.0	12.4	5.0
SD	837	6.7	8.7	10.1	np	5.2
SD	840	6.6	9.1	9.8	11.3	np
NE	722	7.7	9.0	9.7	11.9	4.5 –
NE	852	7.0	9.4	10.0	12.0	5.2
NE	853	np	9.7 +	10.1	12.0	6.5 +
SD	854	np	9.6 +	10.9 +	np	5.5
NE	855	8.9 +	9.4	9.5	11.6	np
Northcentral Nebraska						
SD	757	np	10.1 +	10.2	13.7 +	7.8 + +
NE	721	10.2 + +	11.0 +	10.2	np	np
NE	720	10.7 + +	11.0 +	10.9 +	13.8 +	6.8 +
Central Rocky Mountains						
WY	830	5.5 –	6.3 –	7.6 –	9.0 –	4.7 –
WY	831	np	6.8 –	7.6 –	10.7	4.6 –
WY	848	np	6.8 –	7.4 –	9.7 –	4.8 –
WY	847	np	7.5 –	8.3 –	10.2 –	4.5 –
WY	857	5.4 –	6.1 –	6.8 –	9.6 –	np
NE	844	np	7.4 –	7.2 –	10.6	np
CO	760	4.9 --	5.8 --	6.5 --	9.5 –	4.7 –
CO	761	np	6.5 –	7.2 –	9.9 –	4.9
CO	762	5.9 –	8.3	8.2 –	9.6 –	np
CO	763	np	7.1 –	7.4 –	11.2	4.4 –

Table 3C.—Average tree heights (in feet) for each seed provenance in Southern and Eastern plantations, and symbols to show percentage-of-plantation mean classes[1]—Continued

Seed Provenance Location & No.		Norman OK	Mt. Vernon MO	Columbia MO	Kellog MI	Philipsburg PA
Foothills-Black Hills						
MT	813	np	7.1 –	8.2 –	12.4	4.7 –
MT	815	np	7.6 –	10.1	11.1	5.5
MT	814	np	8.2	8.5	11.4	5.7
ND	702	6.5	8.2	9.2	12.8	4.9
WY	829	np	7.5 –	9.2	10.3 –	4.8 –
WY	832	6.4	9.3	9.6	11.8	5.7
WY	834	np	8.2	8.4	12.4	5.7
WY	835	6.0 –	8.7	9.4	12.5	5.9
WY	836	np	8.5	8.4	11.0	5.7
SD	838	np	7.8	8.8	11.3	4.2 –
SD	839	np	8.2	8.4	12.0	5.4
WY	849	6.0 –	7.8	8.6	10.9	np
WY	850	np	8.4	10.3	12.0	np
NE	851	np	8.5	10.1	12.3	5.6
WY	846	np	8.6	8.5	12.2	np
NE	723	6.8	9.0	9.2	12.0	5.3
NE	845	np	7.7 –	7.8 –	12.1	4.9
NE	759	np	8.9	9.1	12.2	4.9
NE	758	6.9	8.6	9.2	11.3	4.9
NE	856	9.7 + +	9.4	9.6	10.4 –	5.3
CO	858	5.5 –	8.9	8.2 –	12.0	5.2
CO	859	np	9.1	8.5	11.2	np
CO	724	6.2 –	9.0	8.4	11.5	5.8
CO	860	6.8	8.8	9.0	10.4 –	5.0
CO	861	6.5	8.9	8.4	11.5	4.6 –
CO	764	6.4	7.6 –	9.1	11.3	np
CO	765	6.9	9.8 +	10.4 +	11.5	6.2 +
NM	862	6.3 –	9.0	10.1	10.7	6.0 +
NM	863	7.6	10.3 +	9.6	11.4	6.5 +
Southern						
NM	864	7.7	9.7 +	9.8	11.7	np
NM	766	6.8	10.2 +	9.7	12.2	np
NM	767	7.5	10.3 +	10.7 +	10.6	np
NM	768	9.4 + +	11.5 + +	10.2	11.8	np
AZ	869	6.9	9.9 +	10.7 +	13.0	np
Plantation mean height		7.13	8.61	9.37	11.82	5.41
Total sources		40	78	78	75	49

[1] *Explanation: np = none planted; 0 = planted, zero survived.*
Symbols for percentage-of-plantation mean classes:
+ + *greater than 130%*
\+ *111% to 130%*
(mean) 90% to 110%
– *70% to 89%*
-- *less than 70%*

Table 4.—Distribution of percentage-of-plantation mean classes, by seed provenance; and indication of best overall provenances

Provenance No.	Location		Number of Plantations by Percentage-of-Plantation Mean Classes					Best overall performance[1]
			<70%	70-89%	90-110%	111-130%	>130%	
Northwest								
865	Bend	OR	2	3	5			
866	Okanogan	WA	3	3	6	2		
867	Golden Valley	ID	8		3	1		
817	Missoula	MT	1	3	4			
818	Lolo	MT	1	4	1	2		
819	Darby	MT	2	2	5	1		
820	Hamilton	MT	1	3	5	1		
Northern High Plains								
816	Helena	MT			6	10		•
754	Monarch	MT		4	9	3		
753	Windham	MT		1	4			
812	Winifred	MT			11	4		
821	Columbus	MT			10	3	1	
822	Roundup	MT			3	11	2	••
811	Jordan	MT			7	7	2	•
823	Bighorn	MT		1	8	6		
824	Colstrip	MT			7	8	1	•
825	Ashland	MT			2	14		••
727	Fallon	MT		2	7	5		
826	Glendive	MT			10	4	1	
827	Ekalaka	MT			11	5		
828	Camp Crook	MT		1	6	6		
701	Amidon	ND		2	9	4		
703	Ludlow	SD			12	3		
704	Reva	SD			15	2		
833	Aladdin	WY			13	2	1	
837	Lead	SD			11	4	1	
840	Hermosa	SD		2	10	3	1	
722	Chadron	NE		2	11	3		
852	Rushville	NE		1	14	2		
853	Whiteclay	NE		1	9	6		
854	Martin	SD		3	8	4		
855	Merriman	NE			8	7		
Northcentral Nebraska								
757	Rosebud	SD			2	8	5	•••
721	Valentine	NE			3	6	6	•••
720	Ainsworth	NE			2	8	7	•••
Central Rocky Mountains								
830	Sheridan	WY		14	2			
831	Buffalo	WY		12	3	1		
848	Douglas	WY	1	13	2			
847	Wheatland	WY	1	9	3	1		
857	Buford	WY	2	13	1			
844	Pine Bluff	NE	1	9	3			
760	Allenspark	CO	3	14				
761	Boulder	CO	1	9	5			
762	Limon	CO	1	10	5			
763	Woodland Park	CO		8	7	1		

Table 4.—Distribution of percentage-of-plantation mean classes, by seed provenance; and indication of best overall provenances—Continued

Provenance No.	Location		Number of Plantations by Percentage-of-Plantation Mean Classes					Best overall performance[1]
			<70%	70-89%	90-110%	111-130%	>130%	
Foothills-Black Hills								
813	Zortman	MT		4	9	3		
815	Lewistown	MT		3	10	3		
814	Grassrange	MT		1	14			
702	Medora	ND		2	14	1		
829	Dayton	WY		6	10			
832	Recluse	WY		2	13	2		
834	Sundance	WY			12	3	1	
835	Newcastle	WY		3	13	1		
836	Clifton	WY		1	12	2		
838	Hill City	SD		2	13	1		
839	Nemo	SD		1	13	1		
849	Shawnee	WY	1	7	8			
850	Lusk	WY		6	8			
851	Ft. Robinson	NE		4	12			
846	Ft. Laramie	WY	1	1	11			
723	Scottsbluff	NE		3	14			
845	Harrisburg	NE	1	6	8			
759	Dalton	NE	1	2	11	1		
758	Potter	NE		5	11	1		
856	Arnold	NE		4	11	1	1	
858	Ft. Collins	CO	1	11	4			
859	Franktown	CO	2	5	8			
724	Eastonville	CO		7	9			
860	Colo. Springs	CO	3	6	8			
861	Rye	CO	4	6	7			
764	Gardner	CO	1	6	8	1		
765	Gulnare	CO	4		8	4		
862	Raton	NM	5	2	7	1		
863	Ft. Union	NM	5	3	6	2		
Southern								
864	Las Vegas	NM	5	3	5	1		
766	Ruidoso	NM	8		6	1		
767	Mayhill	NM	5	2	5	2		
768	Guadalupe	NM	6		6		2	
869	Ft. Valley	AZ	4	3	4	2		

[1] *** *Best*
** *Good*
* *Acceptable*

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APPENDIX

THE 17 FIELD PLANTATIONS USED IN THIS STUDY,
AND NAMES AND AFFILIATIONS OF COOPERATORS

Plantation Location	Cooperators	Agency
Drumheller, Alberta	Klem Froning	Canadian Forestry Service, Winnipeg
Indianhead, Saskatchewan	J.W. Hamm, Rudy Esau, Gordon Howe	Canada Department Regional Economic Expansion, Indianhead
Towner, N. Dak.	Paul Slabaugh, R.A. Cunningham, James Van Deusen	Rocky Mountain Forest and Range Experiment Station
Grand Rapids, Minn. Morris, Minn. Lamberton, Minn.	Scott S. Pauley Carl A. Mohn	College of Forestry, Univ. of Minnesota, St. Paul
Watertown, S. Dak.	D. Townsend	Big Sioux Nursery, So. Dakota Forestry Department, Watertown
	Paul E. Collins Norman Baer	Department of Horticulture & Forestry, South Dakota State Univ., Brookings
Alliance, Nebr. Halsey, Nebr. Hastings, Nebr.	Ralph A. Read	Rocky Mountain Forest and Range Experiment Station
Plattsmouth, Nebr.	Glenn W. Peterson	Rocky Mountain Forest & Range Experiment Station
Milford, Kan.	Fred Deneke Keith Lynch	Department of Horticulture & Forestry, Kansas State University, Manhattan
Norman, Okla.	Clayton Posey Charles Tauer Robert Gardner	Dept. Forestry, Oklahoma State University, Stillwater and Oklahoma Division of Forestry
Mt. Vernon, Mo. Columbia, Mo.	R. Brooks Polk Henry Stelzer	School of Forestry, Univ. of Missouri, Columbia Missouri Department of Conservation
Kellog, Mich.	Jonathan W. Wright	Dept. of Forestry, Michigan State University, East Lansing
Philipsburg, Pa.	Walter H. Davidson	Northeastern Forest Experiment Station, Kingston

Read, Ralph A. 1983. Ten-year performance of ponderosa pine provenances in the Great Plains of North America. USDA Forest Service Research Paper RM-250, 17 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

A cluster and discriminant analysis based on nine of the best plantations, partitioned the seed provenance populations into six geographic clusters according to their consistency of performance in the plantations.

The Northcentral Nebraska cluster of three provenances performed consistently well above the average in all plantations. These easternmost stands of ponderosa pine along the Niobrara River escarpment in Nebraska from about 101° longitude and eastward, and those in the drainage of the South Fork of the White River near Rosebud, S. Dak. are recommended for tree planting in all Great Plains states.

Keywords: *Pinus ponderosa*, survival, height growth, provenances

Read, Ralph A. 1983. Ten-year performance of ponderosa pine provenances in the Great Plains of North America. USDA Forest Service Research Paper RM-250, 17 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

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*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526

United States
Department of
Agriculture

Forest Service

**Rocky Mountain
Forest and Range
Experiment Station**

Fort Collins,
Colorado 80526

**Research Paper
RM-251**

Effects of Weather and Physiographic Conditions on Temperature and Humidity in Subalpine Watersheds of the Fraser Experimental Forest

Merrill R. Kaufmann

LIBRARY

Dedication

This paper is dedicated to George Wheatley, who served as a Forest Service technician at the Fraser Experimental Forest for 16 years. His persistent attention to detail, often under the harsh winter conditions of the Rocky Mountains, led to the development of climatic and hydrologic records of outstandingly good quality during his tenure.

USDA Forest Service
Research Paper RM-251

April 1984

Effects of Weather and Physiographic Conditions on Temperature and Humidity in Subalpine Watersheds of the Fraser Experimental Forest

Merrill R. Kaufmann, Principal Plant Physiologist
Rocky Mountain Forest and Range Experiment Station[1]

Abstract

Air temperatures were observed at upper elevation and valley weather stations in the subalpine forest zone of the central Rocky Mountains, and canopy temperatures in subalpine watersheds were measured with an infrared thermometer on board a helicopter. During most of the daylight hours, upper elevation air and canopy temperatures were similar to air temperature at a centrally located valley weather station after the valley temperatures were adjusted for a standard adiabatic effect of $-0.0098°C \cdot m^{-1}$. However, clouds and thunderstorm activity introduced considerable local variation in canopy temperature. Slope and aspect had little effect on canopy temperature. Cold air drainage reduced nocturnal valley air temperatures by about 7°C after adjusting for adiabatic effects.

[1]*Headquarters is in Fort Collins, in cooperation with Colorado State University.*

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Effects of Weather and Physiographic Conditions on Temperature and Humidity in Subalpine Watersheds of the Fraser Experimental Forest

Merrill R. Kaufmann

Modeling Implications

The ability to model local differences in temperature and humidity in mountainous regions has considerable appeal for use in process models involving forest consumptive water use, watershed hydrology, tree growth, and air quality. To satisfy this modeling need, this study examined the effects of elevation on air temperature and ambient absolute humidity, and the effects of elevation, slope, aspect, and local weather disturbances on canopy temperature.

Mean hourly air temperature, measured at a valley weather station located at the convergence of several watersheds, was similar to mean air or canopy temperature at higher elevations, up to 8 km away, during most of the daylight hours, after a standard correction for adiabatic effects ($-0.0098°C \cdot m^{-1}$). However, cold air drainage cooled the valley weather station about 7° C during most of the night and early morning. Cold air drainage transported upper-elevation air to the valley weather station, and the minimum ambient absolute humidity measured during the morning was similar to the upper-elevation absolute humidity throughout the day. During summer months, ambient absolute humidity increased diurnally at the valley floor but not at the upper elevations.

Canopy temperature, measured with an infrared thermometer on board a helicopter, also was influenced by elevation, but differences in direct beam irradiance associated with slope and aspect had almost no effect on canopy temperature. Canopy temperature was 4° to 7° C cooler under clouds than under clear sky. However, large local differences in canopy temperature (up to 10° C or more) were observed during thundershower activity. These large local variations preclude the use of off-site weather data for making accurate instantaneous estimates of canopy temperature.

The effect of elevation and cold air drainage and the lack of effect of slope, aspect, and irradiance on canopy temperatures during the summer months probably occurs throughout the central Rocky Mountains, an area dominated by a fairly stable high pressure system.

Introduction

Weather conditions in mountainous regions generally vary over time and space. In the central Rocky Mountains, regional weather phenomena are related primarily to synoptic activity, while localized phenomena are related to convective thunderstorm activity and thermally-induced downslope and upslope air movement.

Knowledge of air temperature and humidity in mountainous areas is becoming increasingly important. For example, calculations of consumptive water use by forests in subalpine watersheds require knowledge of temperature and ambient absolute humidity for each forest stand (Kaufmann 1984a and 1984b). Also, physiographic variables, such as slope, aspect, and elevation, are thought to influence tree regeneration and growth, but the role of site and microclimate effects is difficult to assess without direct knowledge of microclimate conditions.

Attempts to predict temperature in mountainous topography generally have been limited to fairly large-scale situations. For example, Campbell (1972) attempted to predict temperatures in a watershed, using weather records collected at an airport 96 km away. More recently, Running and Hungerford (1983) examined temperature and relative humidity in Montana forests, using airport weather records collected about 32 km away. Their calculations included an empirical adjustment of up to ±2° C to account for possible effects of slope and aspect on temperature.

Weather data have been collected for many years at several locations on the Fraser Experimental Forest in the central Rocky Mountains. In addition, canopy temperature data were collected with an infrared thermometer mounted on board a helicopter flown over the Forest. Together, these data permit an evaluation of long-term and short-term temperature and humidity variation in relation to elevation, slope, aspect, and time of day. This paper evaluates the use of data from a centrally located weather station for predicting air and canopy temperature and ambient absolute humidity in nearby subalpine watersheds in the central Rocky Mountains.

Study Area and Methods

Long-term Weather Records

Studies were conducted at the Fraser Experimental Forest (FEF) 8 km southwest of Fraser, Colo. (Alexander and Watkins 1977). The FEF Headquarters area is at the convergence of the main St. Louis Creek drainage and several smaller drainages (fig. 1), at 2758 m elevation. With the exception of the northeast portions of the main St. Louis Creek drainage, the entire boundary of the 93 km^2 St. Louis Creek watershed is above treeline, at elevations ranging from 3500 to 3900 m.

Permanent weather stations have existed for several decades at the FEF Headquarters area and at the Wind

Tower (WT) site (fig. 1). In 1977, an additional temporary weather station was installed in the Deadhorse watershed (DH in fig. 1). The DH and WT weather stations are at elevations of 3060 m and 3230 m, respectively. The DH station is beneath a mature Engelmann spruce-subalpine fir stand, about 100 m below the ridge separating the Deadhorse and West St. Louis Creek drainages. The WT weather station is in a clearcut, about 20 m from a mature lodgepole pine stand, and about 40 m east of the ridge separating the East St. Louis and Fool Creek watersheds. The FEF Headquarters station is in a 25° opening (originally 30°, measured from the vertical) of a second-growth lodgepole pine stand. Each weather station is equipped with a hygrothermograph and air temperature and maximum-minimum thermometers enclosed in a standard weather shelter. The hygrothermographs were calibrated periodically, using standard techniques to assure that equal conditions yielded similar readings. Weekly minimum hygrothermograph temperatures compared favorably with those observed with the maximum-minimum thermometer, and saturated conditions consistently yielded relative humidities of 100 percent. However, relative humidities measured with hygrothermographs having hair elements are known to be variable, and this limitation in the data is recognized.

Weather records for 1978 through 1981 were used for analyses. For Wednesday of each week of each year, temperature and relative humidity were determined at 2-hour intervals from hygrothermograph records. Data sampling was limited to a 4-year period, because earlier data were not available at the DH weather station. These years appeared to be representative of the range of conditions typically encountered during the past 15 to 20 years. Analyses of weather station data were conducted using the means of the 4-year period for each observation time. The objective of these analyses was to determine if temperature and humidity at the higher elevation sites was systematically related to conditions at the FEF Headquarters. Use of a fairly short period of 4 years is acceptable, because the main objective addresses differences among sites, not long-term characterization of weather conditions.

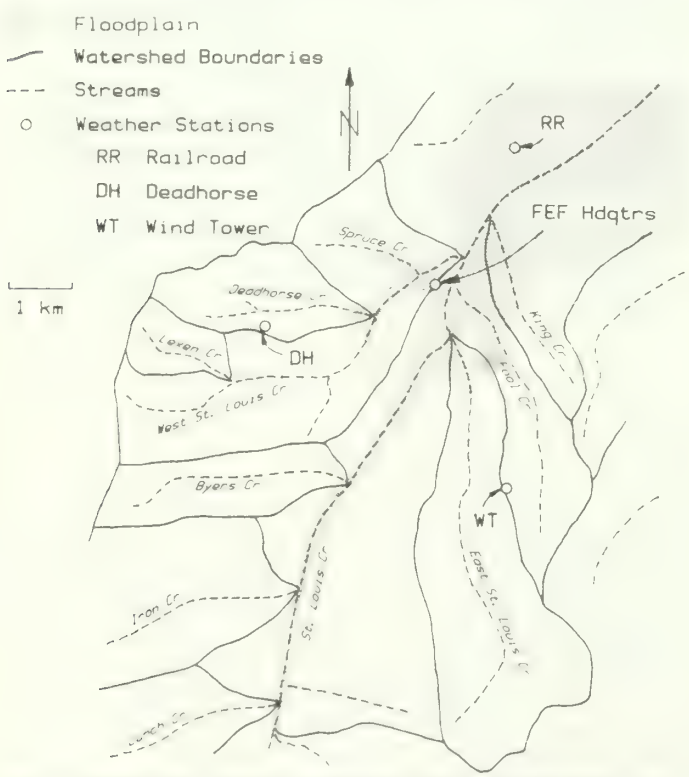


Fig. 1.—Map of the Fraser Experimental Forest showing the major watersheds and locations of weather stations.

Canopy Temperature

In 1982, an infrared (IR) thermometer (Model 210, Everest Interscience[2]), mounted on a helicopter, was used to measure canopy temperatures. The IR thermometer was mounted on a camera pod which extended outside a helicopter door opening. The camera pod also supported a color video camera. Control and recording equipment was placed inside the cabin. The video tape image included time and date. A battery-powered strip chart analog recorder was used to record output from the IR thermometer. The color video image and time recorded on tape were used along with the strip chart IR temperature record to determine IR temperature estimates for specific locations on the ground. The IR thermometer had a pass band of 7 to 16 μm and was operated using an emissivity of 0.98.

The IR thermometer and color video image data were collected on 4 flights per day, on July 13 and August 17, 1982, beginning shortly after sunrise and ending before sunset. These days were typical for the FEF area, beginning with clear weather, followed by partial or complete cloudiness and scattered showers during mid-afternoon.

A similar flight path about 50 km long was followed for each flight. The flight path included transects, in order, across East St. Louis Creek, Fool Creek, lower St. Louis Creek, West St. Louis Creek, Lexen Creek, and Deadhorse Creek (fig. 1). The helicopter was flown at a velocity of about 60 $km \cdot h^{-1}$ and an altitude of about 500 m above the ridges separating the watersheds. The IR thermometer field of view was 20°, yielding a canopy sampling area about 150–225 m in diameter. Slope, aspect, and elevation were determined for 39 specific locations along the flight path, using topographic maps. In addition, the profile of the horizon was determined for each location. These measurements permitted the calculation of direct beam solar irradiance for each site for each flight, with corrections for situations when an intervening ridge obscured the sun (Kaufmann and Weatherred 1982).

Results

Long-term Temperature and Absolute Humidity Relationships

Four-year mean diurnal temperature patterns for each of the weather stations are shown in figure 2 for

[2]*Use of trade names is for the convenience of the reader and is not meant to imply preference or endorsement of USDA to the exclusion of any other product that may be suitable.*

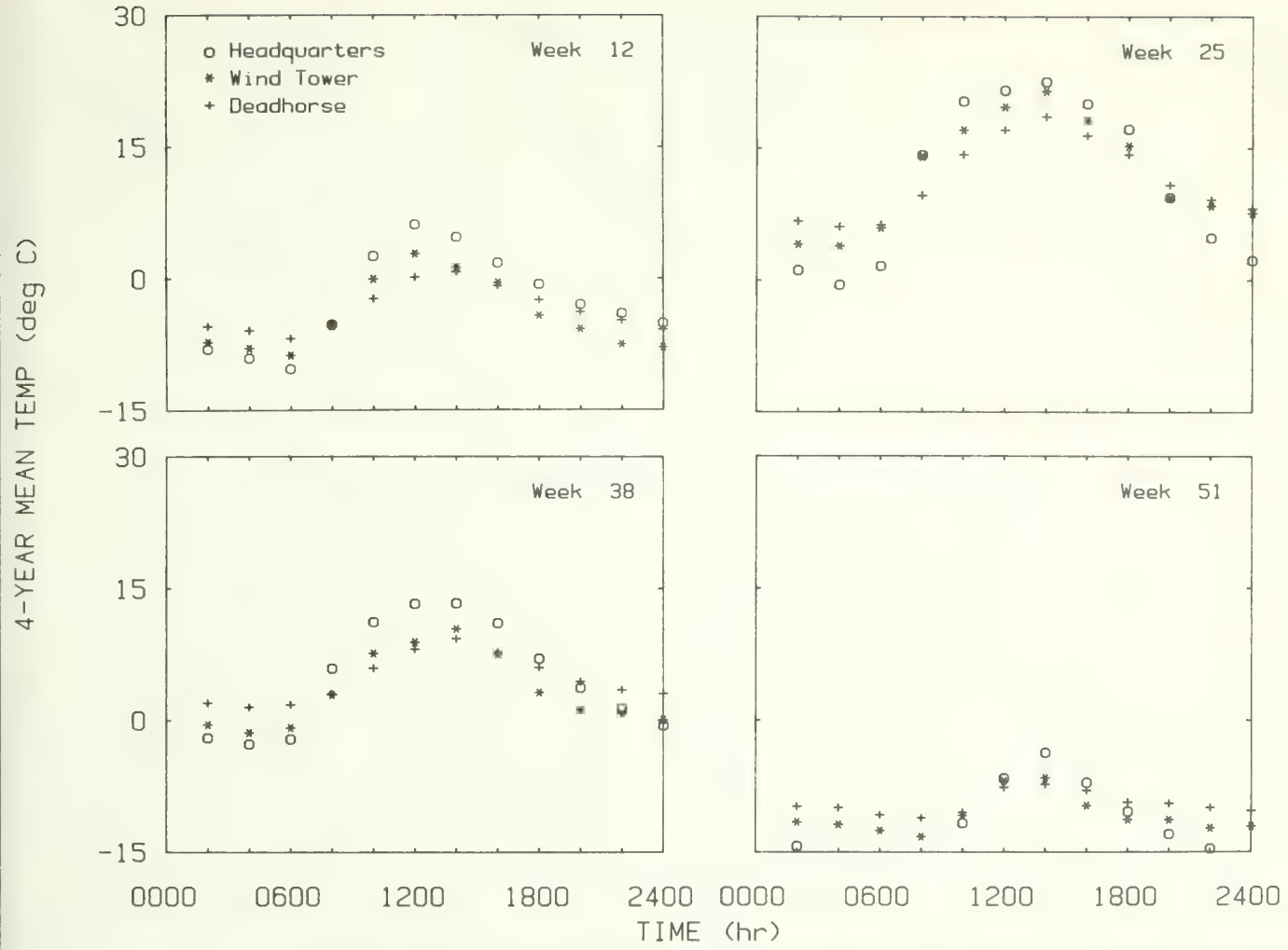


Fig. 2.—Four-year mean diurnal air temperature at FEF Headquarters, Wind Tower, and Deadhorse weather stations. Minimum temperatures at the FEF Headquarters during week 51 (data not shown) were below −15° C.

he weeks corresponding to the solar equinoxes and olstices. During midday, temperature at the FEF Headquarters was consistently higher than at the other two tations. The WT temperature was frequently higher han the DH temperature, even though the WT site was t a higher elevation. The DH station was beneath the orest canopy on a north exposure, which probably resulted in slightly cooler midday temperatures at the instrument shelter near the ground.

At night, air temperature was lower at the FEF Headquarters station than at the higher elevation stations as result of cold air drainage. This pattern was consistent throughout the year. A careful examination of all the veekly data revealed that the cold air drainage effect leveloped 1 to 5 hours after sunset and lasted until 1.5 o 3.5 hours after sunrise.

On that basis, data were sorted for a comparison of DH and WT air temperature with FEF Headquarters air emperature (fig. 3). Nocturnal values are for temperatures observed later than 5 hours after sunset and earlier than 1.5 hours after sunrise. Transition values were observed 1.5 to 3.5 hours after sunrise and 1 to 5 ours after sunset. Diurnal values include observations rom 3.5 hours after sunrise to 1 hour after sunset. The FEF Headquarters temperatures were adjusted for dry adiabatic lapse rate effects at a standard rate of $-0.0098° \cdot m^{-1}$ (Barry 1981). The adiabatic correction accounts for temperature changes of an air mass which expands or shrinks as a result of a change in elevation. Thus the DH temperatures were plotted against [FEF Headquarters temperatures minus 2.96° C], and WT temperatures were plotted against [FEF Headquarters temperatures minus 4.63° C].

After adjusting for adiabatic effects, nocturnal temperatures at the WT or DH weather stations were consistently higher than observed at the FEF Headquarters station (fig. 3, left). The cold air drainage effect reduced the FEF Headquarters temperature an average of about 7° C. During the daytime, however, the temperatures agreed very well after adjusting for adiabatic effects (fig. 3, right). Slightly higher diurnal WT and DH temperatures at low FEF Headquarters temperatures probably reflect a persistent valley temperature inversion or a cold air drainage effect during the daytime in winter months, when the sun angle is very low. Temperatures during the transition periods were variable and tended to fall between the nocturnal and diurnal values (fig. 3, center).

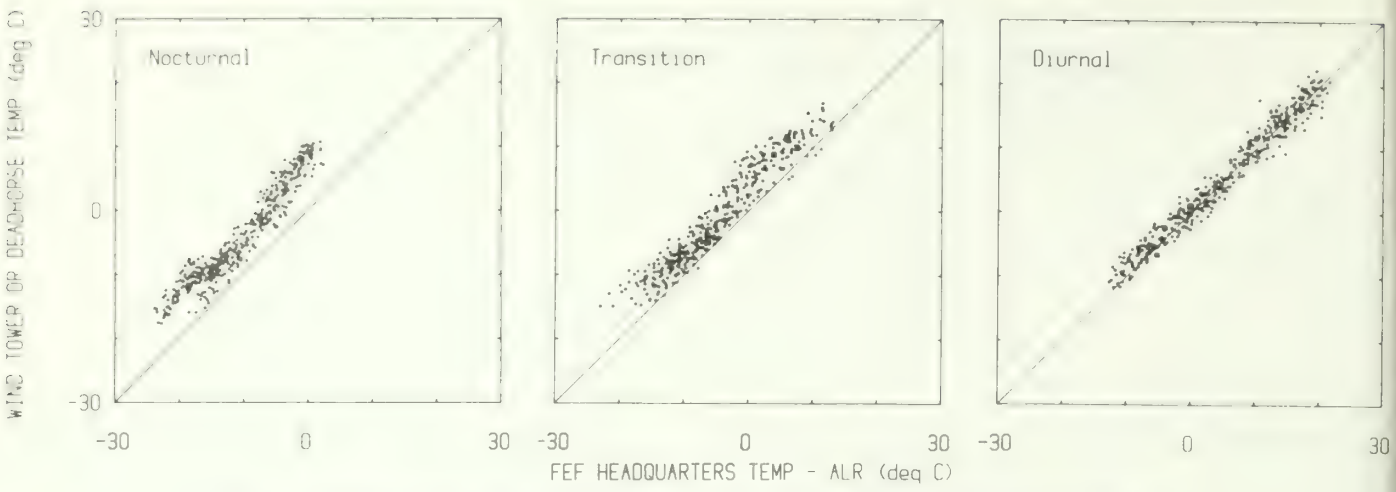


Fig. 3.—Comparision of Wind Tower and Deadhorse weather station temperatures with FEF Headquarters temperatures. The Headquarters temperatures were adjusted for adiabatic lapse rate ($-0.0098°\ C \cdot m^{-1}$).

Ambient absolute humidity was determined from air temperature and relative humidity at each weather station. Four-year mean diurnal patterns of ambient absolute humidity are shown in figure 4 for the same weeks used in figure 2. Two patterns were apparent in the data. First, during midday for weeks 12 to 42, the ambient absolute humidity at the FEF Headquarters was consistently higher than the nocturnal or early morning value. The slight midday increase for the WT station seen in weeks 25 and 38 was observed in only several cases. Second, the minimum ambient absolute humidity observed in the morning at the FEF Headquarters was similar to the ambient absolute humidity observed throughout the day at the higher elevation weather stations.

A comparison of the WT and DH ambient absolute humidities throughout the day and night with the minimum morning ambient humidity observed at the FEF Headquarters is shown in figure 5. Most upper elevation absolute humidity observations (means of four years) were within 1.5 $\mu g \cdot cm^{-3}$ of the minimum FEF Headquarters value. However, when the daytime and nighttime ambient absolute humidites at the FEF Headquarters were compared with the Headquarters morning minimum (fig. 6), observations were stratified during weeks 12 to 42, with diurnal values (0800 to 2000 hr) being as much as 5 $\mu g \cdot cm^{-3}$ higher than the minimum. Ambient absolute humidities below the minimum morning value in figure 6 were observed in the evening. The annual pattern of the minimum morning ambient absolute humidity at the FEF Headquarters is shown in figure 7. Minimum ambient humidities were above 5 $\mu g \cdot cm^{-3}$ in the summer and about 2.5 $\mu g \cdot cm^{-3}$ in the winter.

Canopy Temperature

IR temperatures of the forest canopy during an early morning flight on August 17, 1982, are shown in figure 8. At the beginning of the flight, the solar elevation and azimuth were 22° and 91°, respectively. By the end of the flight, the values had increased slightly to 28° and 96°. Thus the steeper west-facing slopes (e.g., the eastern part of the East St. Louis Creek watershed) were still in shade, but other slopes were already in sunlight. Canopy temperatures for this flight ranged from 4° C in upper East St. Louis Creek to 15.5° C on slopes at lower elevations just north of the FEF Headquarters.

Under the clear conditions encountered for the flight reported in figure 8, the situation was potentially suitable for producing a canopy temperature difference within the East St. Louis Creek drainage caused by differences in irradiance, because the west-facing slopes were still shaded, while the east-facing slopes were receiving direct sunlight. The effect of direct beam irradiance was examined for various drainages, for each flight, by calculating the difference between site temperature within a drainage and the FEF Headquarters weather station air temperature, adjusted for adiabatic lapse rate. This difference was compared with the difference in potential direct beam solar irradiance between the site and FEF Headquarters. A potential direct beam irradiance of 0.0 was assigned in the shade, and an irradiance of 1.0 was assigned when the sun was normal to the surface (Kaufmann and Weatherred 1982).

A comparison of temperature and irradiance differences for the East St. Louis Creek data of figure 8 is shown in figure 9. The FEF Headquarters weather station temperature was 11° C when the East St. Louis Creek data were collected. After adjusting for adiabatic effects, the temperature differences were less than 4° C. On this particular flight, site temperature in East St. Louis Creek was slightly affected by direct beam irradiance ($Y = 1.6 + 2.4X$, $r^2 = 0.44$, where Y is the temperature difference and X is the relative irradiance). In general, however, no significant effect of irradiance on temperature was observed. For almost all flights and drainages, the canopy temperature of stands on different slopes and aspects was unrelated to relative instantaneous direct beam irradiance.

In some instances, local canopy temperatures differed greatly among areas of the FEF sampled in the helicopter IR study. IR temperatures shown in figure 10 were measured during a period when a cold thunderstorm system passed from west to east. IR temperature

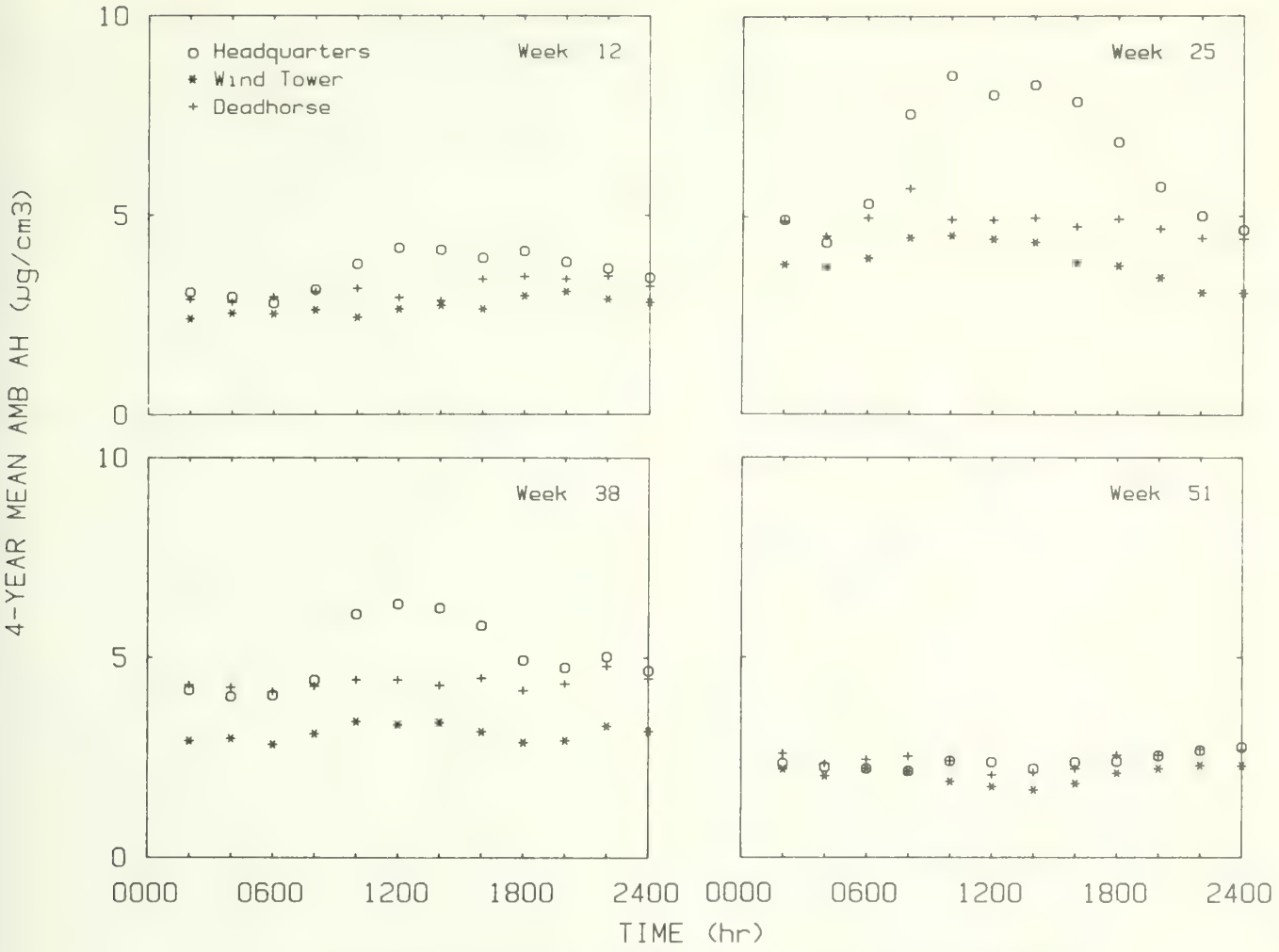
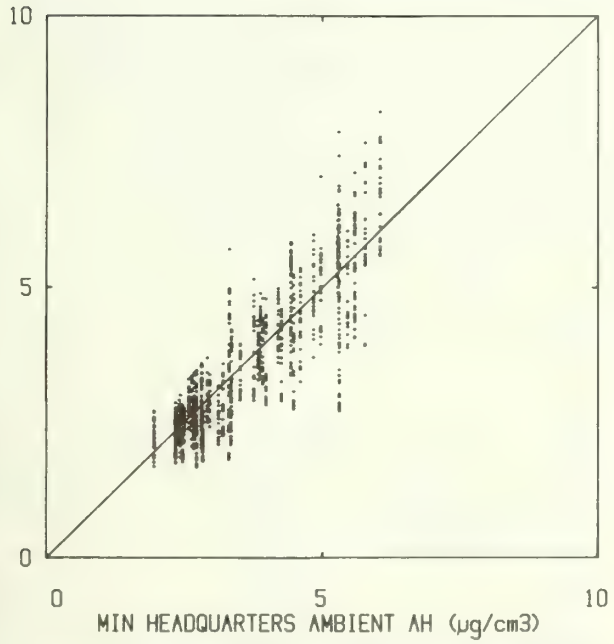


Fig. 4.—Four-year mean diurnal ambient absolute humidity at FEF Headquarters, Wind Tower, and Deadhorse weather stations (1 $\mu g \cdot cm^{-3} = 1\ g \cdot m^{-3}$).



g. 5.—Comparison of Wind Tower and Deadhorse weather station ambient absolute humidities with the morning minimum FEF Headquarters ambient absolute humidity.

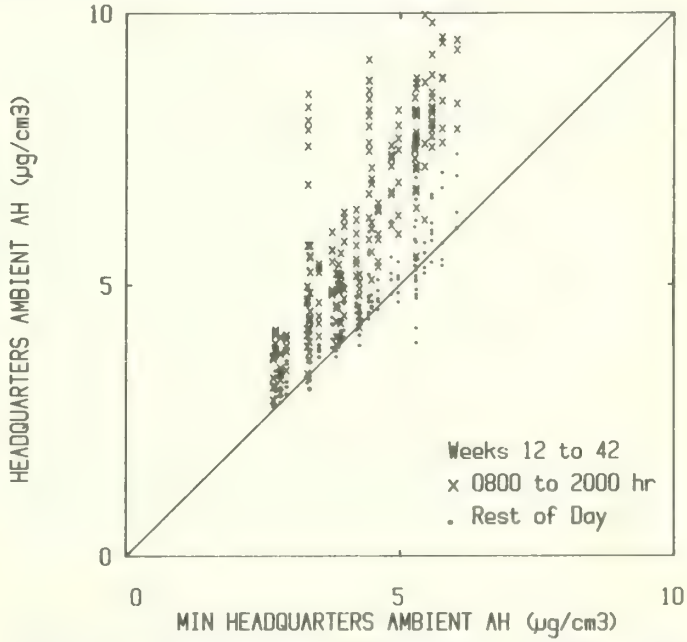


Fig. 6.—Comparison of diurnal ambient absolute humidity at the FEF Headquarters with the morning minimum ambient absolute humidity.

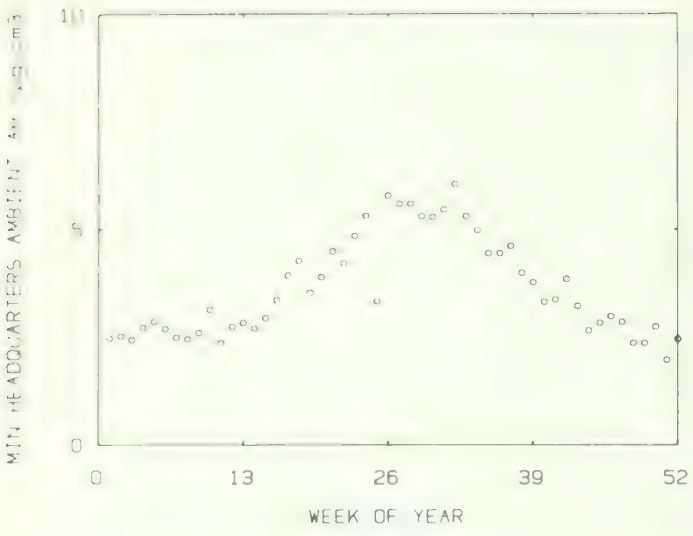


Fig. 7.—Four-year weekly mean minimum ambient absolute humidity at the FEF Headquarters weather station.

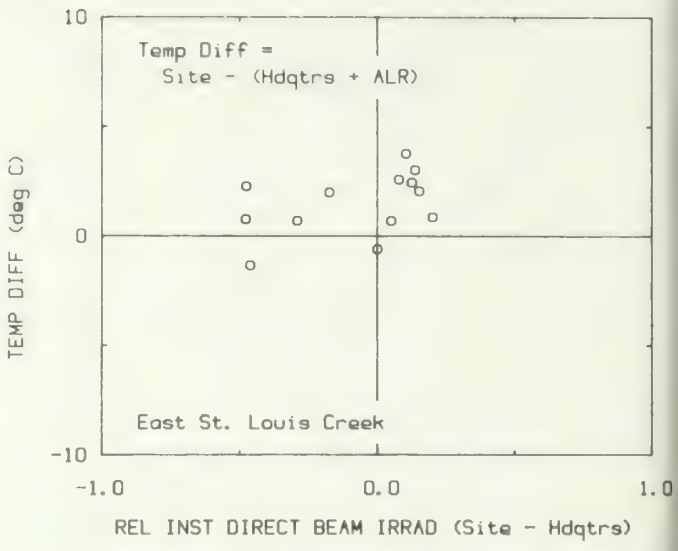


Fig. 9.—Comparison of the temperature difference between the canopy at 13 locations in East St. Louis Creek and the FEF Headquarters weather station temperature (adjusted for adiabatic effects) with the differences in relative instantaneous direct beam irradiance between each site and the FEF Headquarters.

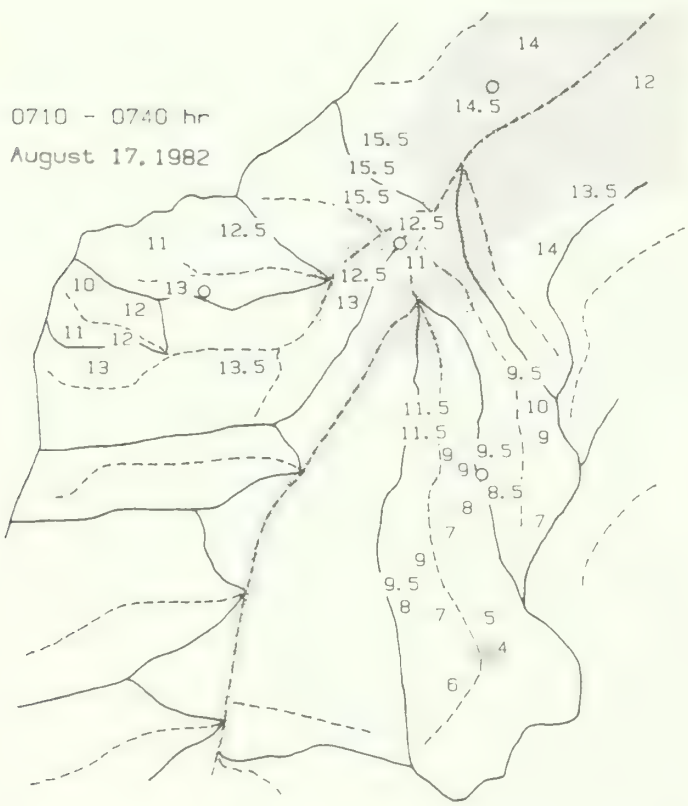


Fig. 8.—Canopy temperatures measured early in the day at various locations on the FEF with an IR thermometer mounted on a helicopter. The two temperatures indicated at the FEF Headquarters correspond to the beginning (top value) and end (bottom value) of the flight.

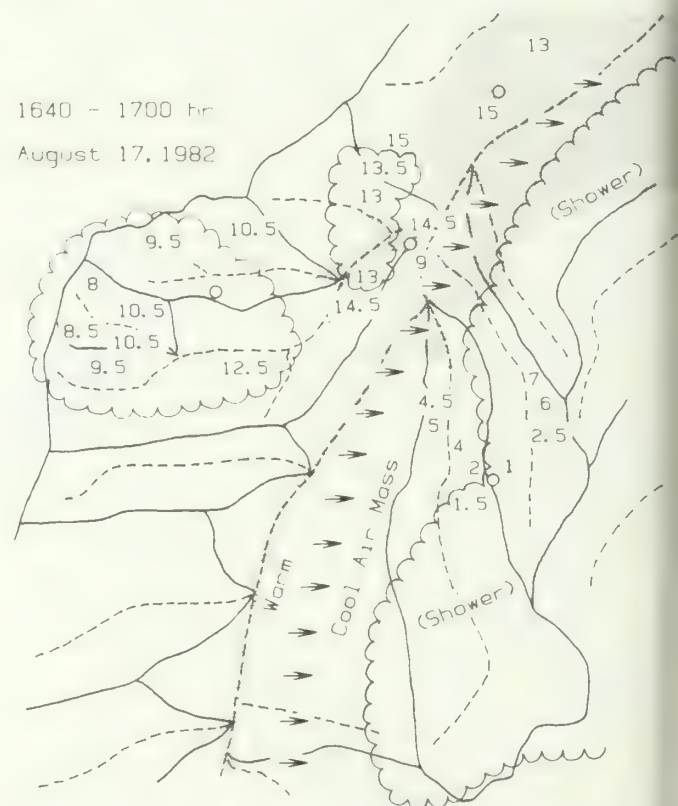


Fig. 10.—Canopy IR temperatures measured during a period of afternoon thundershowers. Cloud positions were determined from color video tapes. During the flight, a thunderstorm system and its associated cool air moved eastward, and the canopy IR temperature at the FEF Headquarters increased from 9 to 14.5° C as the system passed.

at the FEF Headquarters at the beginning of the flight was 9° C, and temperatures in East St. Louis and Fool Creeks were as low as 1.5° C. Forest canopies north and west of the FEF Headquarters were warmer even under a small cloud cover, and by the end of the flight, the FEF Headquarters IR temperature had increased to 14.5°C. Interestingly, the FEF Headquarters weather station air temperature remained at about 15.7° C throughout the

ight period, indicating that canopy temperatures esponded far more rapidly than a protected hygrother-nograph to changes in air mass temperature.

Using graphs similar to figure 9, the temperature dif-erences between the FEF Headquarters weather sta-on and the canopy in outlying areas around the Head-uarters were determined at equivalent direct beam radiances (e.g., temperature differences were deter-ined for irradiance differences of 0.0). For example, ie temperature differences between the East St. Louis reek drainage and FEF Headquarters (adjusted for diabatic lapse rate) at equivalent irradiances was 1.6° C for flight data shown in figure 9. The tempera-ire range observed within watersheds was generally ss than 3° to 5° C, after adjusting for adiabatic lapse ite. The temperature difference at equivalent irra-iances was determined using the mean of adjusted mperatures, except when trends were apparent (e.g., g. 9). In the latter case, lines fitted by least squares ere used to determine the difference at the zero inter-ept of relative irradiance.

Values for the eight flights are given in table 1. Data r clear and cloudy conditions in the watershed units ave been separated, and shaded areas (at low sun ngles) are included with sunlit areas when the sky was ear. During the first flight of each day, when cold air rainage still affected temperature at the FEF Head-uarters, canopy temperatures at the sites were niformly higher than air temperature at the FEF Head-uarters after adjusting for adiabatic effects. On later ghts, however, temperatures differed greatly, with ean site temperatures under clear sky conditions as uch as 3.0° C warmer and 4.3° C cooler than FEF eadquarters temperature. Under cloudy conditions, te temperatures were generally cooler, ranging from 5° C warmer to 11.7° C cooler than FEF Headquarters mperatures.

The mean difference between canopy temperature id FEF Headquarters weather station air temperature r clear and cloudy sky conditions is plotted for each ght in figure 11. Plotted values are the column means

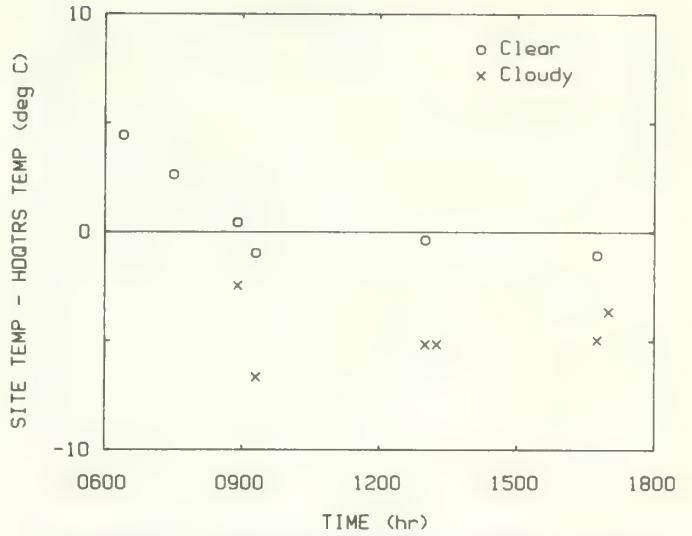


Fig. 11.—Diurnal pattern of the difference between canopy IR temperature and FEF Headquarters weather station air temperature (adjusted for adiabatic effects) for clear and cloudy conditions at canopy IR sites.

for clear or cloudy conditions in table 1. While the means obscure the wide, instantaneous local variation in canopy temperature, they provide an indication of the effect of cloud cover and the cooler air mass frequently associated with clouds on canopy temperature. Canopy temperatures early in the day under clear skies were warmer than FEF Headquarters temperatures adjusted for lapse rate effects; but by mid-morning, canopy temperatures were about 0.5° C cooler than FEF Headquarters temperatures. Cloudy conditions did not exist for either early flight; but in later flights under cloudy skies, the mean canopy temperature was 2° to 7° C cooler than FEF Headquarters temperatures. A possible bias in the data is considered below.

Discussion

The results are consistent with the hypothesis that, in high-elevation regions of the central Rocky Mountains,

Table 1.—Difference between canopy temperature for various areas of the FEF and air temperature (adjusted for adiabatic lapse rate) measured at the FEF Headquarters weather station. Temperature differences were calculated for equivalent irradiances. Times are at the midpoint of the flights which normally lasted about 40 minutes.

Watershed Units	Sky	July 13, 1982 0625 hr	0920 hr	1310 hr	1700 hr	August 17, 1982 0725 hr	0850 hr	1300 hr	1650 hr
East St. Louis Creek									
	clear	+5.3	—	—	—	+1.6	−3.7	−4.3	—
	cloudy	—	−6.7	−11.7	−8.7	—	—	−10.7	−9.3
Fool Creek									
	clear	+4.0	−1.0	—	—	+2.0	+3.0	0	—
	cloudy	—	—	−4.0	−6.0	—	−2.5	−8.0	−7.5
West St. Louis, Lexen, and Deadhorse Creeks									
	clear	+5.0	−0.5	—	—	+3.5	+1.5	—	−2.5
	cloudy	—	—	−3.0	0	—	—	−3.5	−2
Low-lying Areas									
	clear	+3.2	−1.6	—	—	+3.2	+1.0	+3.0	−1.0
	cloudy	—	—	−2.2	−0.2	—	—	+1.5	−1.5

air temperature and humidity are generally related to regional air mass phenomena. However, local phenomena, such as cold air drainage and thundershower activity, can produce pronounced effects. These results probably are applicable throughout the central Rocky Mountains during the summer months, because the area is dominated by a fairly stable high pressure system.

Much of the air temperature difference observed with elevation at the FEF was accounted for by dry adiabatic lapse rate effects. Thus, given suitable temperature observations at a site not influenced by cold air drainage, daytime and nighttime temperatures at different elevations could be predicted simply by adjusting for adiabatic effects. Many weather stations in mountainous regions are on valley floors, however, where they are subject to the effects of nocturnal cold air drainage. The prediction of higher elevation temperatures from valley weather stations must take into account the effects of cold air drainage.

At the FEF Headquarters weather station, cold air drainage reduced the nocturnal temperatures about 7° C. Greater or lesser effects may be observed in other locations, depending on the size of the upper watersheds, width of the valley floor, and specific location of the weather station. Another FEF weather station (Railroad weather station in fig. 1) was located 2 km northeast from the FEF Headquarters, at an elevation only 30 m below the Headquarters weather station but on a much wider floodplain. Weekly minimum temperatures for 1977 were 2.0° C higher at the Railroad weather station than at the FEF Headquarters, suggesting that the cold air drainage effect was more pronounced at the narrower portion of the floodplain found at the Headquarters area, where several watersheds converge. Daytime temperatures were similar at the two weather stations.

The effect of evening onset of cold air drainage on temperature at the FEF Headquarters was more variable than the morning termination. Mornings typically are clear or partly cloudy, except during periods of frontal activity, and solar irradiance increases rather predictably. Afternoons are often cloudy or partly cloudy, and clearing during the evening is irregular, making the evening pattern of radiation balance less uniform from day to day. Irregularity in the onset and duration of cold air drainage probably accounts for the high variability of temperatures between the high and low elevation weather stations during the transition hours (fig. 3).

While the mean elevational differences in temperature were influenced primarily by adiabatic and cold air drainage effects, differences in the daily pattern of absolute humidity at the lower elevation FEF Headquarters weather station appeared to be related to evapotranspiration. Midday increases in ambient absolute humidity observed at the FEF Headquarters occurred during the portion of the year when conditions were favorable for transpiration by the forest canopy (Kaufmann 1984b).

The general lack of ambient absolute humidity increases during the daytime at the higher elevations indicates that the air mass near the ground is continuously mixed with the air mass above the canopy, resulting in fairly stable absolute humidity throughout the day. Furthermore, cold air drainage apparently transports a portion of this air mass to the FEF Headquarters weather station, providing early morning minimum ambient absolute humidities very similar to the ambient humidity of the upper elevation air mass. The diurnal absolute humidity increases observed at the FEF Headquarters during the warmer months suggests that the air mass stagnates on the valley floor during midday.

The comparison of ambient absolute humidity among weather stations does not include a correction for the effects of elevation on pressure. Absolute humidity is a water vapor density term, and changes in pressure affect the density. The pressure differences between the FEF Headquarters weather station and the DH and WT weather stations are 4% and 6%, respectively, under standard atmosphere conditions (List 1971). Air subsidence from the upper weather stations to the FEF Headquarters station would result in an ambient absolute humidity increase of 4% to 6% under nonsaturated conditions, a change not detectable considering the natural variation in ambient absolute humidity (fig. 5) and the uncertainties in its measurement. For larger elevational differences, however, the effect of pressure on absolute humidity probably should be taken into account.

While adiabatic and cold air drainage effects resolve most of the elevational differences in mean air temperature, short-term, local canopy temperature differences during the daytime appear to be closely associated with clouds and thunderstorm activity. On several helicopter flights, data were collected on the fringes of eastward-moving thunderstorms. In the immediate vicinity of the storms, both the canopy surface temperature and the air mass temperature outside the helicopter were sharply reduced. Apparently, convective air movement drew cold upper-level air downward within the storm system. However, air and canopy temperatures rapidly increased again after the storm passed. These short-term events preclude the use of off-site weather data for temperature prediction for specific instances when convective activity exists, although average conditions may still be predicted using long-term weather record means.

Canopy temperatures under clear sky conditions were 0.5° to 1° C cooler during the day than predicted by FEF Headquarters conditions adjusted for adiabatic effects (fig. 11). It is likely that this temperature difference does not exist on average but is the result of a slight bias in data collecting. The decision to fly and collect IR temperature data was made at the FEF Headquarters area landing pad. Flights were begun when rainshowers appeared unlikely; but on several flights, conditions were poorer along the flight path than observed at the FEF Headquarters.

The conclusion that differences in direct beam irradiance associated with slope and aspect had little effect on canopy temperature is supported by several earlier reports. Furman (1978) found that aspect had little effect on the daily maximum temperature observed at a series of paired weather stations on either side of a for-

sted ridge, but the maximum temperature was strongly nfluenced by elevation. Oliver (1975) concluded from isual observations of smoke movement that air within he canopy of a pine forest moved freely, both in random orizontal and in vertical directions, as a result of con- ection. This air movement limits warming of foliage vithin the canopy.

Subalpine forest canopies are generally character- zed by incomplete crown closure. Frequently, tree rowns are found in several layers, and substantial oids exist between trees at various levels within the anopy. Consequently, forced convection by the regional ir mass probably prevents canopy temperatures from eviating significantly from air temperature above the anopy. Furthermore, any tendency for localized heat- ng within portions of the canopy is counterbalanced by igh aerodynamic conductance of the open, irregular anopy, favoring free convective heat loss. However, round surface temperature may be influenced by irra- iance, because mixing is substantially reduced near ne surface. In contrast to subalpine forests, heating vas observed during midday within the canopy of a very ense loblolly pine stand in need of thinning (Hosker et l. 1974).

In summary, mean air and canopy temperatures aried predictably with elevation as a result of diabatic effects. However, local temperatures differed reatly during thunderstorm activity or beneath clouds. Different levels of direct beam irradiance associated vith slope and aspect had little effect on canopy emperature. Nocturnal cold air drainage affected alley air temperatures, but the cold air drainage also ermitted the estimation of upper elevation ambient ab- olute humidity from measurements of the minimum alley absolute humidity measured during the cold air rainage period.

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Air and canopy temperatures of subalpine forests in the central Rocky Mountains were similar to air temperatures at a centrally located valley weather station, after the valley temperatures were adjusted for adiabatic effects and cold air drainage. Thunderstorms caused local temperature differences, but slope and aspect had little effect on canopy temperature.

Keywords: Air temperature, canopy temperature, elevation, slope, aspect, irradiance, absolute humidity, cold air drainage, adiabatic lapse rate, subalpine forests, subalpine watersheds.

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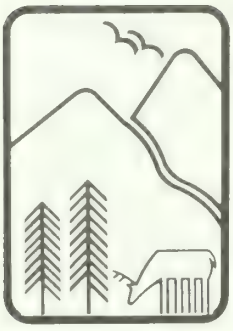
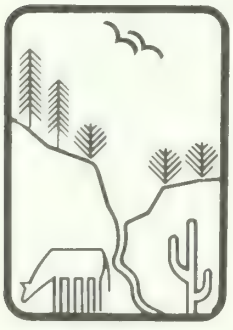


Rocky Mountains



Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
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Documentation and Preliminary Validation of H2OTRANS and DAYTRANS, Two Models for Predicting Transpiration and Water Stress in Western Coniferous Forests

Steven W. Running

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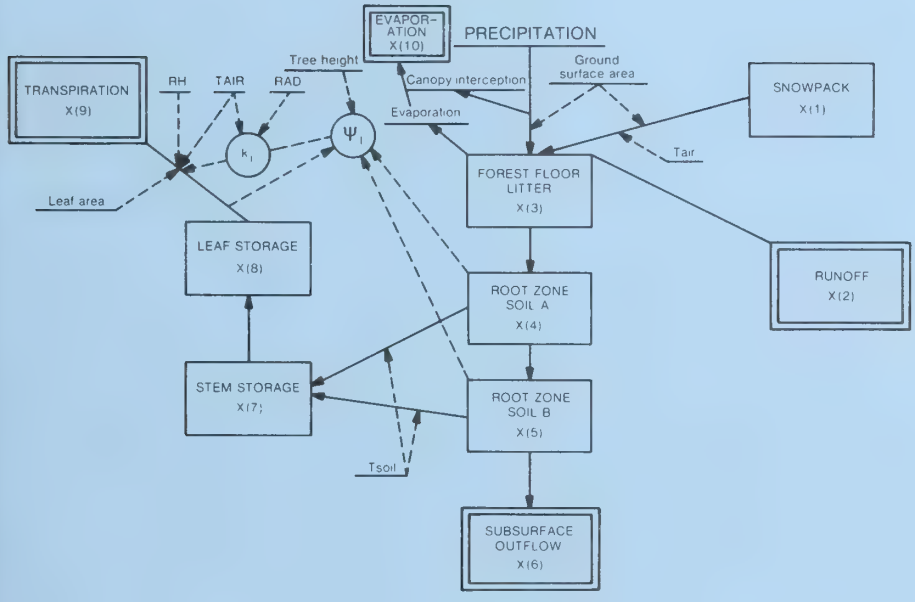
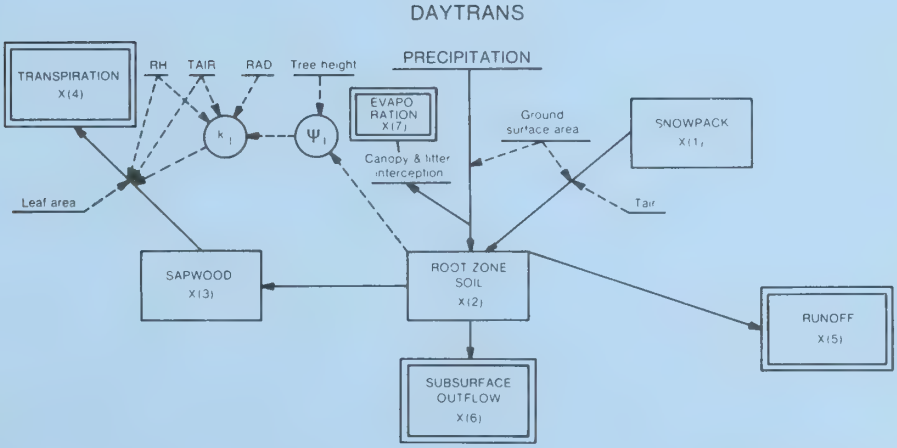
H2OTRANS



DAYTRANS



Acknowledgements

Thanks go to Dr. Richard Waring of Oregon State University for consultation in development of previous versions of this model. Al Brown of Oregon State University provided the general systems processor for the model, and Jeff Graham of the University of Montana helped in executing model runs. Drs. Dennis Knight, Tim Fahey (University of Wyoming), and Steven Grossnickle (Colorado State University) helped in field data collection. This work was partially funded by National Science Foundation grants No. DEB 78-05311 and DEB 80-11024.

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April 1984

Documentation and Preliminary Validation of H2OTRANS and DAYTRANS, Two Models for Predicting Transpiration and Water Stress in Western Coniferous Forests

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Abstract

Two stand-level hydrologic computer models have been developed to study water flow through western coniferous forest ecosystems. The models, H2OTRANS and DAYTRANS, are for hourly and daily timesteps, respectively, and use routine meteorological data. Required parameters include leaf area index, sapwood basal area, and soil storage capacity. The models incorporate rates of snowmelt, precipitation, canopy interception, and litter and soil evaporation. Primary model outputs are transpiration, soil moisture depletion, subsurface outflow, and tree water stress development as measured by leaf water potential and leaf conductance. Complete documentation of all equations is presented, as are the results from an initial validation on lodgepole pine at the Fraser Experimental Forest in Colorado. A sensitivity analysis of the models and a discussion of their range of applicability is also presented.

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H2OTRANS

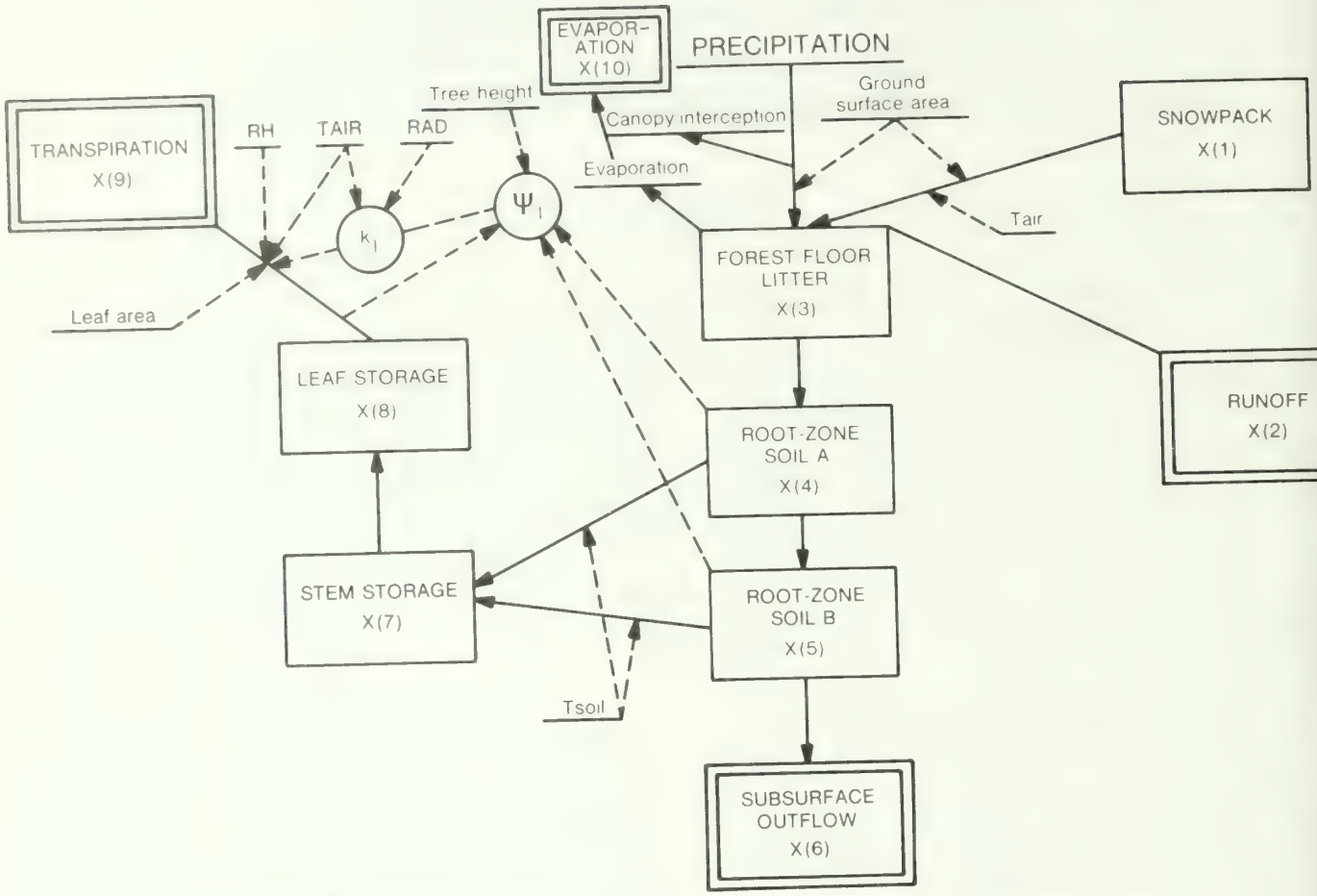


Figure 1.—Compartment diagram and flow linkages for H2OTRANS. The double-lined boxes represent summing compartments.

DAYTRANS

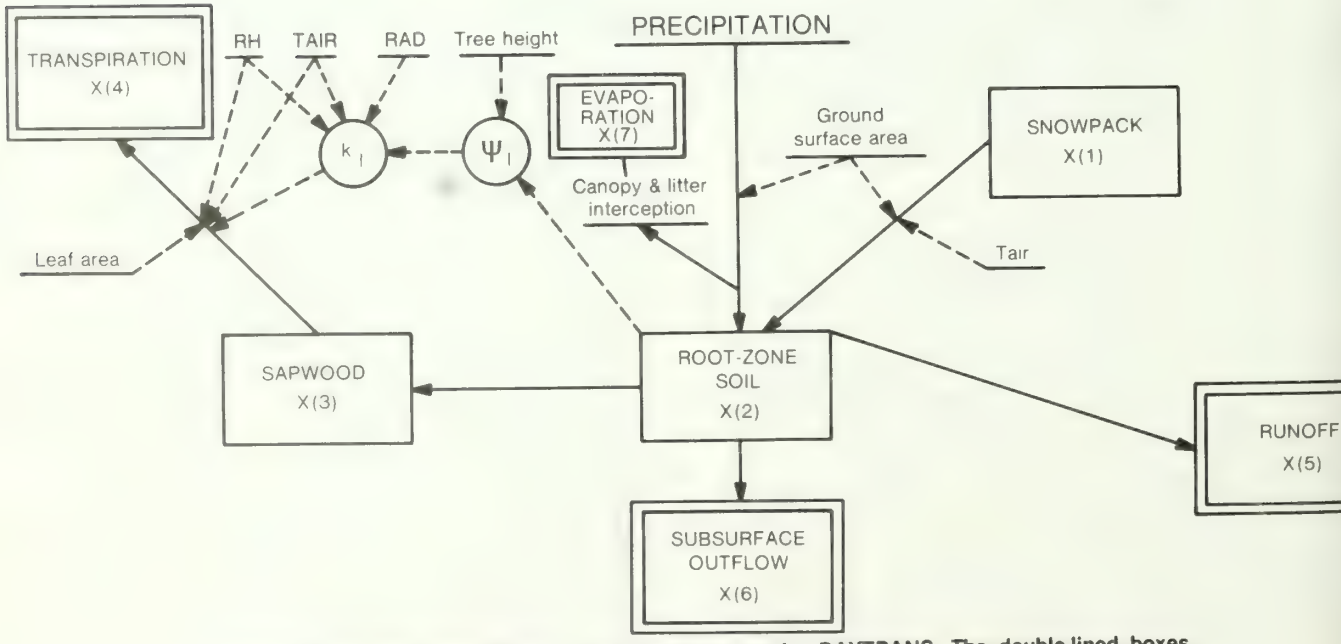


Figure 2.—Compartment diagram and flow linkages for DAYTRANS. The double-lined boxes represent summing compartments.

odel detail. The sequence and a brief description of ıbroutines called follows.

ıbroutine	Description
EADER	Reads in initial information on the number of X, B, G, and Z variables, timestep, and other details that are covered in appendix 2.
COMP	Reads in the Z (driving) variables from a data file, explained in appendix 3.
ROCESS	Calculates all the G (intermediate) variables.
LOW	Uses the G variables calculated in the PROCESS subroutine to calculate the F (flow) variables, which transfer water between X (state) variables.
COMP	Prepares a matrix of computed values for printout.
RINTER	Labels the line printer page, establishes the output format, and prints out all requested parameters.
PDATE	Updates the status of the X (state) variables after each iteration by adding or subtracting water as calculated in the FLOW subroutines.
ERO	Sets the I, Z, F, and G variables to zero after the last iteration in a model run. The last printout then gives a final condition of the X variables.
RROR	Is a library of error statements called when mistakes are made, which identifies the subroutine that caused problems.

H2OTRANS

'ATE VARIABLES—X(i)

State variables or compartments are designated for rts of the stand hydrologic system that have a water rage function. The state of the system can be partial- determined by the location of water in the system at y time. Although the state variables give no indication water transfer in the system, the change in water con- nt of the state variables does. This change is produced the flow functions described that couple the state riables.

A new state variable can be added to the model by signating a new subscripted X in the header file pendix 2). The header file then reads the initial conditions for all state variables. Examples of initial conditions for the state variables are given in the Results section. A list and descriptions of state variables follow.

		Unit
X(1) =	snowpack water content	cm^3
X(2) =	soil surface runoff	cm^3
X(3) =	water storage in forest floor litter	cm^3
X(4) =	available root zone water in Soil Level A	cm^3
X(5) =	available root zone water in Soil Level B	cm^3
X(6) =	subsurface outflow	cm^3
X(7) =	stem sapwood water storage	cm^3
X(8) =	leaf water storage	cm^3
X(9) =	transpiration	cm^3
X(10) =	evaporation, canopy and litter surfaces	cm^3

X(1): The snowpack is defined in terms of the water available for melt into the soil. Because growing season water availability is of greatest importance to this model, X(1) is defined when the snowpack is isothermal at 0° C or "ripe" just prior to spring snowmelt. Any additional snowfall is treated as general precipitation by the model and is not added to X(1). This was done to avoid having to deal with the volume of information needed to calculate an energy budget for the snowpack as developed by Leaf and Brink (1973). Although this simplified snowpack definition is not an accurate estimator of snowpack dynamics, on most years it should be adequate to follow snowmelt into the soil.

X(2): An unlimited summing compartment for surface runoff water that occurs when precipitation or snowmelt exceeds the soil surface infiltration capacity.

X(3): The water content of the forest floor litter. Although this is a small component of the stand water balance, the water content of the forest floor litter is a critical factor in litter decomposition rates, an important part of the terrestrial nutrient cycle.

X(4), X(5): The soil water supply available to the roots is partitioned between X(4) and X(5). Rooting depth and lateral extent must be estimated to compute the total volume of soil tapped by the root systems. While approximate estimation of X(4) and X(5) for a stand is not difficult, exact measurement of these compartment sizes for an individual tree is laborious. X(4) is defined as the upper 50% of the root zone and X(5) as the lower 50%, although this distribution can easily be changed. The main purpose for splitting the root zone water into two compartments was to provide the option of simulating competition between plants of different rooting depth.

X(6): An unlimited summing compartment for water that percolates below the rooting zone. This compartment only receives water when input precipitation or snowmelt continues after X(3), X(4), and X(5) have been filled.

X(7): The water available for transpiration from the stem sapwood of the trees.

X(8): Water stored in the leaves (needles) available for transpiration. This source is small when compared to the rest of the tree water system, but it directly determines leaf water potential (ψ_l). Therefore, it is critical in the control of stomatal response and leaf conductance (k_l).

X(9): Cumulative transpiration from the tree or stand.

X(10): Cumulative evaporation from the stand canopy and litter surfaces.

At each iteration, the current status of each state variable X(i) is printed. In addition, the net change in each state variable from the previous iteration is also printed, designated I(i). For example, X(9) is cumulative transpiration since the beginning of the simulation, and I(9) is the transpiration that occurred in the previous 1-hour timestep.

FLOW FUNCTIONS—F(i,j)

The convention of F(i,j) is that X(i) is the state variable from which water is withdrawn; X(j) is the compartment to which water from X(i) is added. If i = j, this denotes water input from a source external to the model entering X(i) or output to an unmonitored sink. The F(i,j) notation couples the correct state variables, while the G variables shown are the calculated magnitude of flow between X(i) and X(j) at any iteration. The equations used to calculate the G variables are described in a subsequent section. A list and descriptions of flow functions follow.

	Unit
F(3,3) = G(50) – G(53)	cm^3
F(1,3) = G(51)	cm^3
F(3,2) = G(54)	cm^3
F(3,4) = G(55)	cm^3
F(4,5) = G(56)	cm^3
F(5,6) = G(57)	cm^3
F(8,9) = G(18)	cm^3
F(7,8) = G(62)	cm^3
F(4,7) = G(67)	cm^3
F(5,7) = G(68)	cm^3
F(10,10) = G(53) + G(58)	cm^3

F(3,3): Precipitation into the model from the exterior source (driving variable) minus canopy interception that does not reach the forest floor. Also subtracts litter surface evaporation from X(3).

F(1,3): Snowmelt input to the forest floor litter compartment.

F(3,2): Surface runoff that occurs when precipitation and/or snowmelt exceeds the soil surface infiltration capacity.

F(3,4): Water that flows into the root zone Soil A compartment, X(4), after the forest floor litter is saturated (i.e., after X(3) is at capacity).

F(4,5): Water that enters after X(4) has reached capacity is cascaded to X(5).

F(5,6): When X(3), X(4), and X(5) are all at capacity, additional water input to the system is routed to subsurface outflow, X(6), from X(5).

F(8,9): Moves water from leaf storage, X(8), to th transpiration sink, X(9).

F(7,8): Water withdrawn from internal tree sapwoo storage to help satisfy the water demand generated b F(8,9) and the deficit created in X(8).

F(4,7), F(5,7): When a water deficit is created in X(by transpiration, F(8,9), this demand is met by roo water uptake from the two rooting zone soil reserve X(4) and X(5).

F(10,10): Canopy and litter evaporation.

Note that water movement into the soil state var ables, X(1) through X(6), is basically input or donor cor trolled. Water withdrawal from the system, (transpira tion) is an output demand with donor control.

DRIVING VARIABLES—Z(i)

These variables are input from an exterior data file Appendix 3 presents this data file format. Precipitatio and soil temperature are input once every 24 hours; th other meteorological variables are entered hourly. Thi was done because precipitation is rarely recorded mor than once daily by most installations, and soil tempera ture at 20 cm changes slowly. The 24-hour precipitatio is input into the model as 1/4 of daily total at hours 1, 2 3, and 4 of each day. This limits the effects of short bu severe thunderstorms. In particular, surface runoff F(3,2), rarely occurs. Precipitation could easily be inpu hourly, and I recommend this modification, if hourly data can be recorded. The other variables either can b recorded once each hour, typically on the hour, or b full-hour averages. A list of driving variables follows.

	Unit
Z(1) = Julian date	day
Z(2) = precipitation	cm day^{-1}
Z(3) = air temperature	°C
Z(4) = relative humidity	%
Z(5) = soil temperature (20 cm depth)	°C
Z(6) = incoming shortwave radiation	ly min^{-1}
Z(7) = hour of day	h

AUXILIARY CONSTANTS—B(i)

The constant parameters are values entered into th model for use in various computations; they do no change throughout the model run. These can includ stand physical dimensions, conversion constants, an empirical coefficients used to calculate intermediate (G variables. All B parameters are specified and entere into the program by the HEADER file, explained in detai in appendix 2. Examples and derivations of values use for the B constants are covered in the Results sectio because many are site-specific. A list of auxiliary con stants follows.

		Unit
B(1)	= snowpack melt coefficient	cm $°C^{-1}$
B(2)	= maximum soil surface infiltration rate	cm h^{-1}

B(3) = water storage capacity of forest floor litter, X(4) cm^3

B(4) = maximum available water storage in root zone Soil A, X(4) cm^3

B(5) = maximum available water storage in root zone Soil B, X(5) cm^3

B(6) = canopy interception coefficient cm LAI^{-1}

B(7) = maximum available water storage in stem sapwood, X(7) cm^3

B(8) = maximum available leaf water storage in X(8) cm^3

B(9) = tree or stand total leaf area (not projected area) cm^2

B(10) = ground surface area cm^2

B(11) = average midcrown tree height m

B(12) = maximum canopy average leaf conductance (k_l) cm s^{-1}

B(13) = spring minimum predawn leaf water potential ($B\psi_l$) MPa
NOTE: Throughout the model, water potential is treated as a positive value for mathematical simplicity.

B(14) = leaf osmotic potential (and stomatal closure threshold) MPa

B(15) = sapwood basal area cm^2

B(16) = leaf water depletion coefficient h^{-1}

B(17) = stem and soil water exchange coefficient h^{-1}

TERMEDIATE VARIABLES—G(i)

The intermediate variables are used for a variety of eliminary calculations in the model. Because each w variable is controlled by many factors, it is not ssible to write one equation representing all condi-ns. Consequently, G variables are used to provide re manageable intermediate computations. Often the variables will represent specific processes of impor-ce in the model, such as the control of leaf conduct-e by incoming radiation. Because all G variables ve a unique subscript, they do not have to be used se-ntially. For clarity it is useful to group G variables t are performing similar computations. A brief index G variables precedes their detailed documentation.

G(1) - G(9): water storage and water content calculations
G(10) - G(19): leaf conductance and transpiration calculations
G(50) - G(59): soil water input calculations
G(60) - G(69): tree water uptake calculations
G(70) - G(79): leaf water potential, flow resistance T/PT ratio.

Description of G Variables

Water Storage and Water Content

G(1) = absolute humidity deficit (g cm^{-3})

$$G(1) = S3(Z(3), Z(4))$$

where
Z(3) = air temperature,
Z(4) = relative humidity.

This statement sends air temperature and relative humidity to Function S3. The function calculates absolute humidity deficit and returns it to G(1).

G(2) = leaf area index, LAI (m^2 m^{-2})

$$G(2) = B(9)/B(10)$$

where
B(9) = total stand (or tree) leaf area, all surfaces,
B(10) = total stand (or tree) ground surface area.

G(3) = available water fraction in X(3), forest floor litter (cm^3 cm^{-3})

$$G(3) = X(3)/B(3)$$

where
X(3) = present water content of the forest floor litter,
B(3) = water capacity of the forest floor litter.

Converting available water in compartments to a fraction allows easy changing of compartment sizes through the Header file without reprogramming each G variable.

G(4) = available water fraction in X(4), the upper soil root zone (cm^3 cm^{-3})

$$G(4) = X(4)/B(4)$$

where
X(4) = present water content of the upper soil root zone,
B(4) = water capacity of the upper soil root zone.

G(5) = available water fraction in X(5), the lower soil root zone (cm^3 cm^{-3})

$$G(5) = X(5)/B(5)$$

where
X(5) = present water content of the lower soil root zone,
B(5) = water capacity of the lower soil root zone.

G(6) = averaged available water fraction in the total soil rooting zone (cm^3 cm^{-3})

$$G(6) = (G(4) + G(5))/2$$

where
G(4) = available water fraction in the upper soil root zone,
G(5) = available water fraction in the lower soil root zone.

G(7) = available water fraction in X(7), stem storage (cm^3 cm^{-3})

$$G(7) = X(7)/B(7)$$

where

X(7) = present stem sapwood water content,
B(7) = maximum available stem sapwood water storage.

Leaf Conductance and Transpiration

G(10) = predawn leaf water potential, $B\psi_l$ (–MPa)

$$G(10) = AMAX1\ (B(13),\ 0.2/G(6) + 0.01 \cdot B(11),\ 0.0)$$

where

AMAX1 = an intrinsic FORTRAN function that chooses the maximum from a set of values in the parentheses,
B(13) = spring minimum predawn leaf water potential,
0.2 = an empirical coefficient used to generate the curve in figure 3,
G(6) = averaged total available water fraction,
0.01 = hydrostatic gradient constant (MPa m^{-1}),
B(11) = midcrown tree height.

This statement calculates the predawn leaf water potential ($B\psi_l$) as a function of available root zone soil water in X(4) and X(5) (fig. 3). This type of relation between $B\psi_l$ and soil water content has been found numerous times in various plant communities (Sucoff 1972, Hinckley and Ritchie 1973, Branson et al. 1976, Huzulak 1977). The function basically combines the well-known curvilinear relationship between soil water content and soil water potential (Heth and Kramer 1975, Nnyamah and Black 1977), and the linear relationship between soil water potential and predawn leaf water potential (Hinckley et al. 1978, Drew and Ferrell 1979, Sala et al. 1981).

This treatment of the soil-plant interaction is rather superficial and yet, appears adequate for the purposes of this model. Implicit in the equation is the moisture tension release curve of a well-drained sandy loam. The equation would not easily incorporate a soil of radically stratified physical characteristics. In that instance, it would be best to define separate soil compartmen (X(4), X(5), etc.) and treat each soil horizon individually

This equation also assumes root distribution adequa to extract water from the entire defined rooting zone s compartment. Consequently, both the definition of ava able water in rooting zone soil (X(4) and X(5)) and a co rect response function for G(10) (fig. 3) is necessary f the model to correctly predict the magnitude and timi of soil moisture depletion and tree water stress develo ment. For accurate results, this response curve (fig. should always be checked in a new area with field mea urements of predawn leaf water potential plotte against soil water content.

G(11) = light-saturated leaf area index ($m^2\ m^{-2}$)

$$G(11) = 10.0 \cdot (1.0 - EXP(-4.6 \cdot Z(6)))$$

where

10.0, 1.0, –4.6 = curve-fitting coefficients,
EXP = exponential,
Z(6) = incoming shortwave radiation.

Stomata of many trees do not fully open until incomin shortwave radiation reaches around 10% of full su light (Davies and Kozlowski 1974, Dykstra 1974, Hinc ley et al. 1975, Watts et al. 1976, Hinckley et al. 1978 So, G(11) calculates how much leaf area index is abo the radiation threshold of 0.1 ly min^{-1} at the curre radiation level Z(6). A typical Beer's Law exponenti decrease in radiation as it passes vertically through th canopy is assumed (fig. 4). The most difficult and lea measured parameter is the attentuation coefficient radiation as it penetrates different forest canopies (No man and Jarvis 1975, Jarvis et al. 1976). I used an a tenuation analysis from Kira et al. (1969), also used b J. Rogers (pers. comm.) in his general watershed hydr logic model for the IBP Coniferous Forest Biome. No that his analysis attenuates radiation as a function LAI, not vertical height, eliminating need for data abo canopy geometry. However, implicit in this treatment the assumption of a relatively continuous canopy. semiopen stand of large trees may have deep canopie but an overall low stand LAI. Also, no attempt is made t adjust radiation effects for diurnal sun-angle changes a is done in more rigorous canopy radiation models (Nor man and Jarvis 1975).

G(12) = k_l, radiation correction fraction (dim.)

$$G(12) = 1.0 - (G(2) - G(11))/G(2)$$
$$IF(G(11)\ .GT.\ G(2))\ G(12) = 1.0$$

where

1.0 = unity multiplier for k_l reduction,
G(2) = leaf area index,
G(11) = light-saturated leaf area index,
.GT. = a FORTRAN statement, "greater than."

If the light-saturated leaf area index calculated i G(11) is larger than the actual LAI of the stand, then n light-induced k_l reduction occurs, and G(12) computes 1.0 multiplier for k_l. If light is limited to a portion of th canopy, G(12) calculates what fraction of the stand LA is light-saturated and uses that fraction as a multiplie for the k_l final calculation. Consequently, if 70% of th canopy is receiving 0.1 ly min^{-1} or greater, radiation is multiplied by 0.7 to reduce the canopy averag

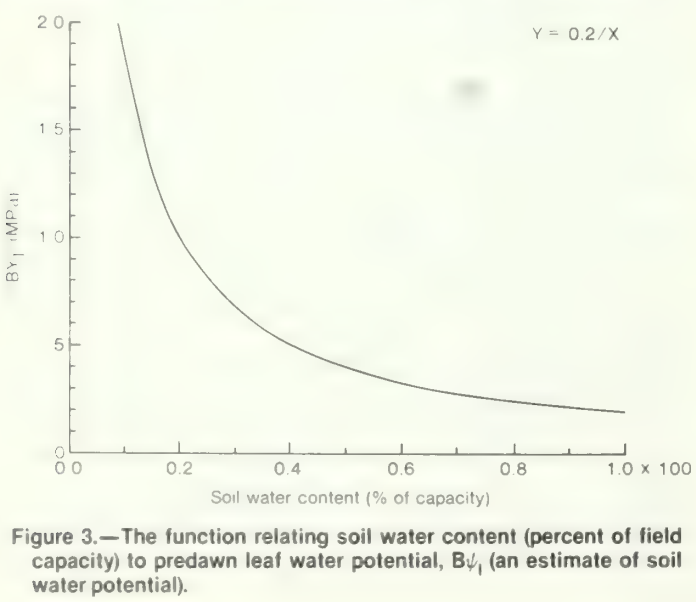


Figure 3.—The function relating soil water content (percent of field capacity) to predawn leaf water potential, $B\psi_l$ (an estimate of soil water potential).

cause of the canopy that has closed stomata. Note t this assumes a $k_l = 0$ for leaves under the radiation eshold, but more precise estimates of k_l at low-light els would become complicated and would exceed our owledge of canopy light attenuation theory and short-m stomatal fluctuations under low-light conditions.

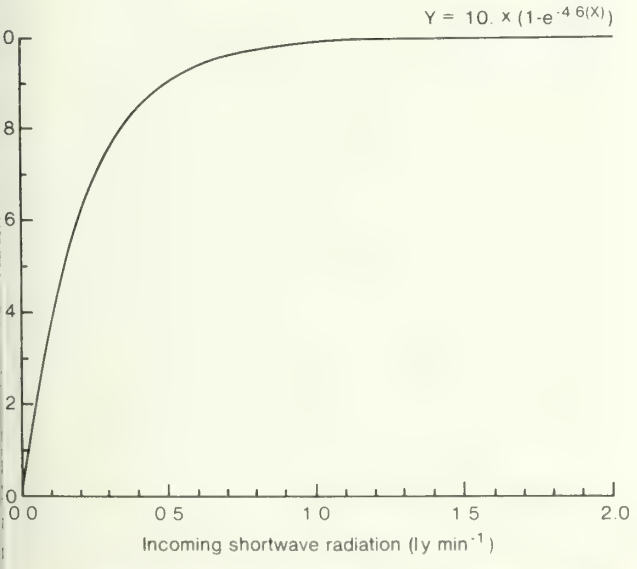
13) = k_l, predawn leaf water potential correction (cm sec^{-1})

```
G(13) = AMAX1 (B(12) – (B(12)/(B(14) – B(13)))·(G(10)
                – B(13)),0.005)
        IF(G(10) .LT. B(13)) G(13) = B(12)
```

ere
- 3(12) = maximum canopy average k_l,
- 3(13) = spring minimum predawn leaf water potential,
- 3(14) = stomatal closure threshold,
- G(10) = predawn leaf water potential, $B\psi_l$,
- .005 = k_l at complete stomatal closure,
- .T = a FORTRAN statement "less than."

This function reduces maximum k_l as soil water is pleted (fig. 5). Maximum daily k_l has been found to be direct function of $B\psi_l$, G(10). This function was first monstrated on *Pseudotsuga menziesii* in Oregon by nning (1976) and duplicated on *Pinus contorta* in Colo-lo by Running (1980), both on sapling-size trees. hough I hypothesize that the relationship between and maximum k_l is fundamental, different species d different tree sizes may require a modified response rve. Consequently, B(12), B(13), and B(14) were made ernally changeable. The ratio B(12)/(B(14)-B(13)) pro-es the slope of the k_l reduction for any range of k_l and 4) entered.

The 0.005 cm s^{-1} minimum k_l has been generally nd for a variety of conifers (Hinckley et al. 1978). It ould be remembered that the k_l value calculated here presents a canopy average for leaves of different ages ough all crown heights.



ure 4.—Describes the leaf area index, LAI, that would receive in-oming shortwave radiation in excess of 0.1 ly min^{-1} (the tomatal opening threshold) at any level of incoming radiation.

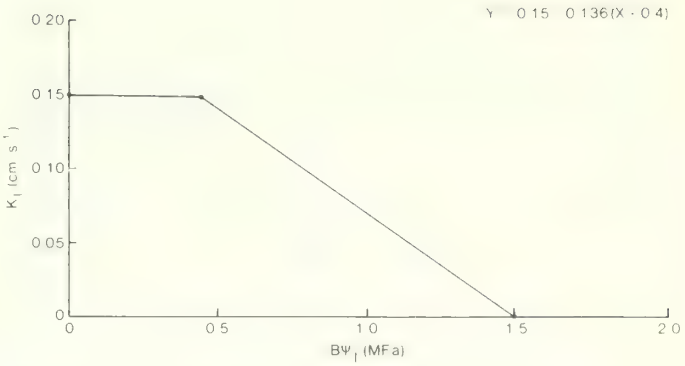


Figure 5.—The reduction in maximum leaf conductance, k_l, resulting from increasing plant water stress (predawn leaf water potential, $B\psi_l$).

G(14) = k_l, humidity correction (cm s^{-1})

```
G(14) = G(13) – (G(13)·0.05·(G(1)·10^6 – 4.0))
        IF(G(14) .LE. 0.0) G(14) = 0.005
```

where
- G(13) = k_l, leaf water potential correction,
- 0.05 = k_l, humidity deficit slope coefficient (fig. 6),
- G(1) = absolute humidity deficit,
- 4.0 = initial humidity reduction threshold (μg m^{-3}),
- .LE. = a FORTRAN statement, "less than or equal to,"
- 0.005 = minimum k_l.

There is much evidence that k_l is reduced by low atmospheric humidity, regardless of ψ_l. As absolute humidity deficit calculated in G(1) increases, the maximum k_l from G(13) is linearly reduced as a fraction of the original (G(13)) leaf conductance. Theoretical analysis of this phenomenon is reported in Lange et al. (1971), Sheriff (1977), Edwards and Meidner (1978), and Losch and Schenk (1978). The function in G(14) is based on field data on western conifers reported by Running (1976, 1980), Kaufmann (1976), and Tan et al. (1977).

From reviewing the above papers, Running (1980) found that this function reasonably represents field data collected on *Pseudotsuga menziesii, Pinus ponderosa, Pinus contorta, Picea sitchensis, Picea engelmannii,* and *Tsuga heterophylla.* It appears that when humidity reduction in k_l is analyzed as a fraction of daily maximum k_l, a fairly generalized equation, such as in G(14), can be developed.

Note that with this equation structure the G(14) equation is independent of maximum k_l, which is input from B(12) through G(13). Also, at an absolute humidity deficit above 25 μg cm^{-3}, the second equation sets k_l = 0.005 cm s^{-1}, a general minimum leaf conductance substantiated by many studies. Trees in very arid climates may be able to retain stomatal opening at these humidity deficits.

G(15) = k_l, air temperature correction (cm s^{-1})

```
G(15) = S1(Z(3), Z(7),G(14))
```

where
- S1 = a special function called from elsewhere in program that uses Z(3), Z(7), and G(14) values to calculate G(15),

Z(3) = air temperature,
Z(7) = hour of day,
G(14) = k_l, humidity reductions.

This equation calls special function S1 where the effect of air temperature of k_l is calculated and returned as G(15).

G(16) = k_l, final canopy average (cm s^{-1})

$$G(16) = G(15) \cdot G(12)$$

where
G(15) = k_l,
G(12) = radiation limiting fraction.

This computes the final canopy average k_l by the radiation reduction fraction from G(12).

To summarize k_l control in the model: G(13) computes leaf (and soil) water potential effects. G(14) adds humidity effects to k_l. G(15) adds air temperature effects. Finally, G(16) adds radiation control from G(12). The overall hierarchy of k_l control from strongest to weakest is (1) radiation, (2) leaf water potential or $B\psi_l$, (3) humidity or ABSHD, and (4) air temperature.

G(17) = transpiration flux density (g cm^{-2} s^{-1})

$$G(17) = G(16) \cdot G(1)$$

where
G(16) = k_l, canopy average,
G(1) = absolute humidity deficit (ABSHD).

Transpiration flux density is the product of k_l and ABSHD. This equation is equivalent to the diffusion equation used by Tan et al. (1978).

$$E = (PCp/LV)((e_s - e_a)/(r_s + r_a))$$

where
E = transpiration rate (g cm^{-2} s^{-1}),
P = air density (g cm^{-3}),
Cp = specific heat of air (J g^{-1} $°C^{-1}$),
L = latent heat of vaporization (J g^{-1}),
V = psychrometric constant (mb $°C^{-1}$),
e_s = saturation vapor pressure (mb),
e_a = ambient vapor pressure (mb),
r_s = stomatal resistance (s cm^{-1}),
r_a = aerodynamic resistance (s cm^{-1}).

Figure 6.—The reduction in maximum leaf conductance, k_l, resulting from increasing absolute humidity deficit.

In the equation in G(17), P, Cp, L, V, e_s, and e_a are all subsumed into G(1), the absolute humidity deficit. Both Tan et al. (1978) and the research reported here ignored r_a for the reason that r_a is typically 20-100 times smaller than r_s in coniferous forests (Smith 1980), and would require input of vertical profiles of windspeed. Also, $k = 1/r_s$ is used.

Midday humidity in western forests is so low that the humidity deficit component of the Penman - Monteith equation far exceeds the radiation component of evaporative demand (Jarvis et al. 1976, Luxmoore et al. 1981). Consequently, the diffusion equation used in G(17) to compute stand transpiration and used by Tan et al. (1978) in their transpiration model varies from the more theoretically satisfying Penman - Monteith equation by less than 2%. The diffusion equation is used because of its simplicity and reduced demand for meteorological input variables.

G(18) = hourly stand transpiration (g h^{-1})

$$G(18) = G(17) \cdot B(9) \cdot 3600$$

where
G(17) = transpiration flux density,
B(9) = stand leaf area,
3600 = seconds per hour.

G(18) equals F(8,9), water transfer from leaf storage X(8), to the atmospheric transpiration sink, X(9).

Soil Water Input

G(50) = effective precipitation (cm^3 h^{-1})

$$IF(Z(7) .GT. 4.) Z(2) = 0.0$$
$$G(50) = AMAX1((Z(2)/4 - B(6) \cdot (B(9)/B(10))) \cdot B(10), 0.0)$$

where
Z(7) = hour of day,
Z(2) = precipitation,
B(6) = canopy interception coefficient,
B(9) = stand leaf area,
B(10) = ground surface area.

This function translates the one-dimensional precipitation data into volumetric units and subtracts canopy interception based on leaf area index, B(9)/B(10). The result is equal to F(3,3), the precipitation input into X(3).

Precipitation Z(2) is divided by 4 to estimate input from the once-daily precipitation record and is entered between 0000 and 0400 hours. This may underestimate instantaneous rainfall intensity and overestimate interception losses. With modern data-loggers, hourly precipitation should be recorded to avoid these artificial problems. Canopy interception of precipitation is treated proportionally to LAI using an interception coefficient which, in effect, is leaf surface water storage. Nearly two-thirds of the annual precipitation in a Rocky Mountain lodgepole pine forest falls as snow, outside of the growing season (Alexander and Watkins 1977). Summer rainfall typically is in the form of short thundershowers that do not recharge the rooting zone soil and are a modest component of the stand hydrologic balance. Consequently, while more elaborate canopy in-

eption and evaporation models are available (Rutter
l. 1971, Murphy and Knoerr 1975, Stewart 1977,
d and Deans 1978), a more accurate treatment of in-
eption processes does not seem warranted here.
s algorithm assumes that the canopy is dry at each
rly iteration, which overestimates interception loss
ing an extended rainfall event. Also, no attempt is
le to retard transpiration while the canopy is wet.
vever, this problem is reduced implicitly because,
r a thundershower, evaporative demand is greatly
ıced until the intercepted water has evaporated.
pplication of this model to sites having more signifi-
t summer precipitation should entail collecting hour-
recipitation data and possibly calculating a canopy
gy balance to predict evaporation of intercepted
ipitation.
ne AMAX1 function with a 0.0 limit is used to protect
equation from calculating a negative precipitation.

1) = snowmelt ($cm^3\ h^{-1}$)

$$G(51) = AMIN1(Z(3) \cdot B(1) \cdot B(10), X(1))$$
$$IF(Z(3)\ .LE.\ 0.0)\ G(51) = 0.0$$

re
3) = air temperature,
1) = snowpack melt coefficient,
10) = ground surface area,
1) = snowpack water content.
is equation melts the snowpack in X(1) as a function
ir temperature, Z(3), and a melt coefficient, B(1),
multiplies it by ground area, B(10), to give
metric water input to X(3). The degree-day snow-
t equation was basically derived from data in the
Army Corps of Engineers Snow Hydrology report
6). This approach is only reasonable for spring
wmelt of a ripe isothermal pack. More rigorous
dels of snowmelt do complete energy balances for the
wpack (Leaf and Brink 1973, Colbeck and Ray 1979).
s increased complexity seems unnecessary for a
del whose focus is primarily summer water stress
elopment. The melt coefficient, B(1), should be recali-
ed for use in other regions. G(51) is equal to F(1,3).

2) = litter vapor conductance ($cm\ s^{-1}$)

$$G(52) = EXP(5.0 \cdot (G(3) - 1.0))$$

re
0, 1.0 = curve-fitting coefficients,
3) = litter water fraction.
is equation calculates a water vapor conductance
for evaporation of water from the forest floor litter.
approach is derived from classic evaporation and
sion principles (Lee 1980), and is similar to the litter
oration function of CFBMG (1979), except that a
able conductance term, G(52), was calculated as a
tion of litter water content. It assumes a conduct-
e of 1.0 cm s^{-1} from a saturated litter layer, with an
onential decrease in conductance as the litter sur-
dries, increasing boundary layer resistance (fig. 7).

3) = litter evaporation ($cm^3\ h^{-1}$)

$$G(53) = G(52) \cdot G(1) \cdot B(10) \cdot 3600$$

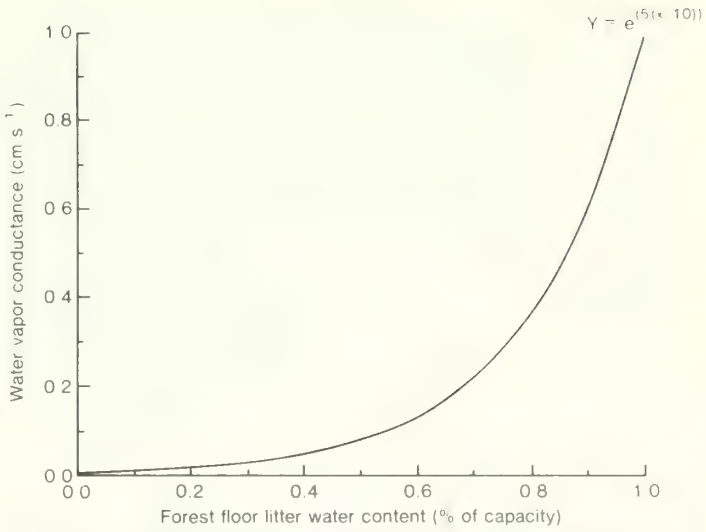


Figure 7.—As water content of the forest floor litter is depleted, the water vapor conductance is reduced by this function.

$$IF(G(3)\ .LE.\ 0.0)\ G(53) = 0.0$$
$$IF(X(1)\ .GT.\ 0.0)\ G(53) = 0.0$$

where
G(52) = litter vapor conductance,
G(1) = absolute humidity deficit,
B(10) = ground surface area,
3600 = seconds per hour,
G(3) = litter water fraction,
X(1) = snowpack water content.

Litter evaporation is driven by atmospheric demand, absolute humidity deficit, G(1), and is limited by G(52) as the surface dries. Volumetric litter evaporation per hour is determined by multiplying by B(10) and 3,600 s/hour. This approach is simple and can be calibrated easily. Model adjustments would best be made in the G(52) response curve of figure 7. Because this equation only quantifies mass transfer considerations of evaporation theory, water loss from an open surface subjected to a significant diurnal radiation load may be underestimated. G(53) is subtracted from the water input to X(3) by F(3,3).

G(54) = surface runoff ($cm^3\ h^{-1}$)

$$G(54) = AMAX1((G(50) + G(51) - (B(2) \cdot B(10))), 0.0)$$

where
G(50) = precipitation,
G(51) = snowmelt,
B(2) = maximum soil surface infiltration rate,
B(10) = ground surface area.

If precipitation, G(50), plus snowmelt, G(51), exceed the soil surface infiltration capacity, B(2)·B(10), runoff occurs to X(2). This water transfer is done in F(2,2). However, overland flow on forested land is rare (Anderson et al. 1976). In addition, unless precipitation data is input hourly instead of the present daily data, there is little potential for overland flow in the model.

G(55) = litter compartment water transfer ($cm^3\ h^{-1}$)

$$G(55) = AMAX1((G(50) + G(51) - G(53) - G(54)) - (B(3) - X(3)), 0.0)$$

where
G(50) = precipitation,
G(51) = snowmelt,
G(53) = litter surface evaporation,
G(54) = surface runoff,
B(3) = water storage capacity of forest floor litter,
X(3) = current water content of forest floor litter.

This function does a mass balance of the forest floor litter storage, X(3), to determine the volume of water flow from X(3) into X(4). Inputs of precipitation, G(50), and snowmelt, G(51), are added; outputs of litter evaporation, G(53), and surface runoff, G(54), are subtracted. If X(3) is not at capacity, the deficit, B(3)-X(3), is first refilled, with the excess input water then cascading into X(4). The result equals F(3,4).

G(56) = root zone Soil A water transfer ($cm^3\ h^{-1}$)

$$G(56) = AMAX1(G(55)-(B(4)-X(4)),0.0)$$

where
G(55) = litter compartment water transfer,
B(4) = maximum water storage in root zone Soil A,
X(4) = current water storage in root zone Soil A.

As in G(55), a mass balance is done for X(4). Input from X(3) is added as G(55), water used to refill any deficit, B(4)-X(4), is subtracted, and the remainder cascaded to X(5). G(56) equals F(4,5).

G(57) = root zone Soil B water transfer ($cm^3\ h^{-1}$)

$$G(57) = AMAX1(G(56)-(B(5)-X(5)),0.0)$$

where
G(56) = root zone Soil A water transfer,
B(5) = maximum water storage in root zone Soil B,
X(5) = current water storage in root zone Soil B.

Again, input from X(4) is added until any deficit in X(5) is filled, B(5)-X(5). The excess water cascades into the subsurface outflow compartment, X(6), with an unlimited capacity. G(57) equals F(5,6).

Inherent in the mass balances of G(55), G(56), and G(57) are two assumptions. First, they do not allow soil supersaturation. All water in excess of field capacity is routed to the lower compartment. A second related assumption is that they effectively treat saturated hydraulic conductivity of the soil as infinite. At each hourly iteration, excess water is immediately routed to the lower compartment with no lag time. This was done to reduce the model requirements for soil physical data, and because these rather short-term phenomena were of small importance to seasonal water stress development. In some areas and for certain applications, this part of the model may require more sophisticated treatment.

G(58) = canopy evaporation ($cm^3\ h^{-1}$)

$$G(58) = Z(2)/4.\cdot B(10)-G(50)$$

where
Z(2)/4. = precipitation, entered from 0000 to 0400 hours,
B(10) = ground surface area,
G(50) = effective precipitation.

Water Withdrawal

G(60) = leaf water storage, current available (cm^3)

$$G(60) = B(8)\cdot(1.-G(10)/B(14)+B(13)/B(14))$$

where
B(8) = maximum available leaf storage,
G(10) = predawn leaf water potential, $B\psi_l$,
B(14) = leaf osmotic potential, stomatal closure threshold,
B(13) = spring minimum $B\psi_l$.

Recent research on the role of internal water storage in plant water relations (Hellkvist et al. 1974, Robert 1977, Richter 1978, Waring and Running 1978, Waring et al. 1979, Running 1980c) has demonstrated that leaf water content and leaf water potential are directly related. This equation reduces available leaf water storage as predawn ψ_l increases, G(10), and approaches the leaf osmotic potential, B(14), where stomata close.

G(61) = leaf storage exchange rate ($cm^3\ h^{-1}$)

$$G(61) = X(8)/B(16)$$

where
X(8) = leaf water storage,
B(16) = leaf water depletion coefficient.

Although available leaf water storage has been studied in some detail, the short-term exchange rates of water from leaf tissue has not. The flow of water through leaf tissue greatly exceeds the diurnal net change in leaf water content. This function, taken from Running (1980c) on *Pinus contorta*, limits the hourly exchange rate of water from leaf storage, X(8), and is necessary for both biological and mathematical stability of leaf water exchange.

G(62) = stem water transport ($cm^3\ h^{-1}$)

$$G(62) = 0.0$$
$$IF(G(61)\ .GE.\ G(18))\ G(62) = AMAX1(G(60)-X(8),G(18)/B(16))$$
$$IF(G(61)\ .LT.\ G(18))\ G(62) = G(18)-G(61)$$

where
G(61) = leaf storage exchange rate,
G(18) = hourly stand transpiration,
G(60) = current leaf water storage,
X(8) = leaf water storage,
B(16) = leaf water depletion coefficient.

This function computes the water flow from X(7) to X(8) by determining how much of the transpiration demand can be satisfied by X(8), because in order to retain mass balance in the model, all transpiration demand must be met. When demand generates water stress by water depletion in various parts of the model, transpiration is reduced in future iterations by feedback control on k_l. If exchangeable water in X(8), G(61), exceeds the transpiration demand G(18), then G(62) can either refill previous X(8) deficits G(60)-X(8) or a fraction of the demand G(18)/B(16). In the more normal case, where demand G(18) exceeds supply G(61), then G(62) requests flow from X(7) to cover all demand above exchangeable supply in X(8), G(18)-G(61). G(62) equals F(7,8).

6) = stem storage exchange rate ($cm^3\ h^{-1}$)

$$G(66) = X(7)/B(17)$$

ere
(7) = stem water storage,
(17) = stem water exchange coefficient.

rom research by Waring and Running (1978), War- et al. (1979), and Running (1980c), there is data on ee different coniferous species showing sapwood er depletion rates. This function limits the amount of er that can be withdrawn from X(7) on any one itera- by a rate constant B(17).

7) = root zone Soil A water uptake ($cm^3\ h^{-1}$)

67) = AMIN1(G(62)–G(66), (B(7)–X(7)/B(17), X(4)/B(17))
ere
(62) = stem water transport,
(66) = stem storage exchange rate,
(7) = maximum available stem water storage,
(7) = current stem water storage,
(17) = stem and soil water exchange coefficient,
(4) = root zone Soil A soil water.

ow from X(4) into X(7) is determined by the demand, 2), minus any that can be satisfied by X(7), G(66). If e is no demand (i.e., at night), but X(7) is not full, flow come into X(7) to fill this deficit, B(7)-X(7), subject to B(17) exchange coefficient. The final control of F(4,7) ake is that water withdrawal cannot exceed the nangeable supply in rooting zone Soil A, X(4)/B(17). 7) equals F(4,7).

8) = root zone Soil B water uptake ($cm^3\ h^{-1}$)

G(68) = AMIN1(G(62)–G(66)–G(67), (B(7)–X(7))/B(17))
ere
(62) = stem water transport,
(66) = stem storage exchange rate,
(67) = root zone Soil A water uptake,
(7) = maximum available stem water storage,
(7) = current stem water storage,
(17) = stem water exchange coefficient.

milar to G(67), G(68) is the water requirement ded to fulfill transpiration demand minus supply al- ly contributed by stem water, G(66), and by X(4), 7). This function chooses the minimum of two calcu- d flow potentials—the remaining demand or the nangeable supply in X(7). If X(7) is not full, the deficit -X(7) can also be filled subject to the exchange coef- ent limit B(17).

Water uptake is controlled by a feedback loop where moisture depletion, X(4) and X(5), increase predawn t moisture stress, G(10), which reduces k_l, G(13), and spiration, G(18), thus reducing water uptake de- nd, G(67) and G(68).

transpiration demand exceeds supply in X(4), X(7), X(5), which could only happen after months of pro- sive tree water stress and depletion of soil moisture ero, X(5) would become negative. This means the tree tand died of water stress!

G(69) = total root system water uptake ($cm^3\ h^{-1}$)

$$G(69) = G(67) + G(68)$$

where
G(67) = root zone Soil A water uptake,
G(68) = root zone Soil B water uptake,

Total root system uptake is combined for use in calculating diurnal leaf water potential in G(73).

Leaf Water Potential, Flow Resistances, Transpiration Ratios

G(70) = root resistance, soil temperature influences (MPa $\mu g^{-1}\ cm^{-2}\ s^{-1}$)

$$IF(Z(5)\ .LE.\ 0.0)\ G(70) = 10.0$$
$$IF(Z(5)\ .GT.\ 0.0)\ G(70) = 1.0/Z(5)$$

where
Z(5) = soil temperature,
10.0 = a high soil resistance limit when soil temperature is less than 0° C; also protects the fraction from division by 0.0.

Recent studies have found root resistance to water uptake to increase rapidly as soil temperature approaches freezing (Babalola et al. 1968, Havranek 1972, Kaufmann 1975, Running and Reid 1980). These effects have been found in different conifer species and are partially physiological in nature. Increasing water viscosity explains only a part of the observed increase in flow resistance. The function in figure 8 approximates the data of Running and Reid (1980) on *Pinus contorta* and of Kaufmann (1975) on *Picea engelmannii*.

G(71) = flow resistance, soil water influences (MPa $\mu g^{-1}\ cm^{-2}\ s^{-1}$)

$$G(71) = -0.28 + 2.0 \cdot G(10)$$

where
–0.28, 2.0 = empirical coefficients to fit data from Running (1980b),
G(10) = predawn leaf water potential.

The importance of flow resistance in the overall development of water potential gradients in coniferous trees has been quantified using a root excision technique (Roberts 1977, Running 1980b). Root resistance appears to increase as a direct function of decreasing soil water potential. This function increases flow resistance as predawn leaf water potential increases (negative ψ values are treated as positive numbers in the model, fig. 9). These data were from trees 3-5 m tall. Both the relaive and absolute influence of root resistance probably will be different on larger trees.

G(72) = total root resistance (MPa $\mu g^{-1}\ cm^{-2}\ s^{-1}$)

$$G(72) = G(70) + G(71)$$

where
G(70) = root resistance, soil temperature influences,
G(71) = root resistance, soil water influences.

G(73) = leaf water potential, ψ_l (MPa)

$$G(73) = AMIN1(G(10) + G(72) \cdot (G(69) \cdot 278.0/B(9)),\ B(14))$$

where

G(10) = predawn leaf water potential,
G(72) = total root resistance,
G(69) = total root water uptake,
278.0 = combines the constants $10^6 \mu g\ g^{-1}$ and 3,600 s h^{-1},
B(9) = stand leaf area,
B(14) = leaf osmotic potential, stomatal closure threshold.

From plant water relations theory:

$$T = (\psi_{soil} - \psi_{leaf})/R_{total}$$

where

T = transpiration rate,
$\psi_{soil}-\psi_{leaf}$ = the soil to leaf water potential gradient,
R_{total} = the total resistance to water flow between the soil and leaf.

This equation can be rearranged to predict ψ_{leaf} as follows: $\psi_{leaf} = \psi_{soil} + R_{total} \cdot T$ (ψ treated as positive value) and has been used in a number of studies (Elfving et al. 1972, Kaufmann and Hall 1974, Hinckley et al. 1978). However, as pointed out by Waring and Running (1976, 1978) and Running (1980c), system capacitance confuses this equation. I have modified the equation by substituting G(10) for ψ_{soil} and by using G(69) instead of transpiration G(18) for water flux. This allows water to be withdrawn from internal reservoirs before ψ_l begins to increase and produces the diurnal ψ_l hysteresis typically found in trees (Jarvis 1975, Running 1980a). Using root water uptake, G(69), to generate ψ_l also agrees with studies showing the major component of overall flow resistance, and ψ gradient development to be at the soil-root interface (Robert 1977, Running 1980b).

Development of ψ_l is limited in this equation to B(14), the stomatal closure threshold, which typically varies between 1.5 and 2.3 MPa for temperate conifers (Hinckley et al. 1978). Under severe stress, trees can exceed this value, although the model cannot presently handle that circumstance.

G(76) = transpiration/potential transpiration ratio (dim.)

$$G(76) = G(16)/B(12)$$

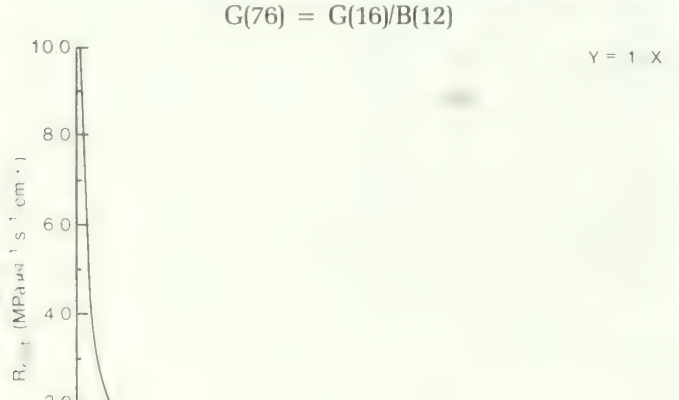


Figure 8.—Decreasing soil temperature produces a nonlinear increase in root water flow resistance.

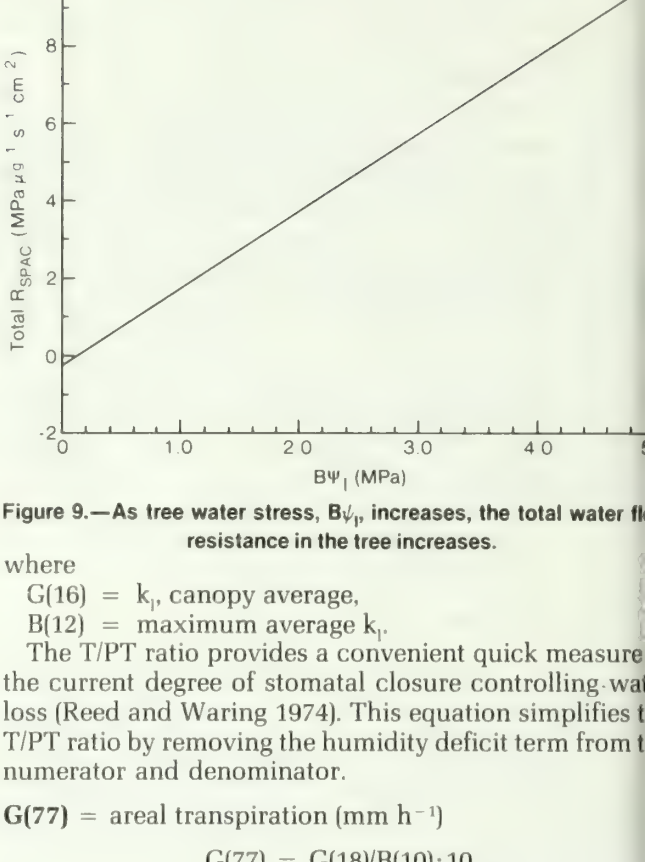


Figure 9.—As tree water stress, BΨ$_l$, increases, the total water fl resistance in the tree increases.

where

G(16) = k_l, canopy average,
B(12) = maximum average k_l.

The T/PT ratio provides a convenient quick measure the current degree of stomatal closure controlling wa loss (Reed and Waring 1974). This equation simplifies T/PT ratio by removing the humidity deficit term from numerator and denominator.

G(77) = areal transpiration (mm h^{-1})

$$G(77) = G(18)/B(10) \cdot 10$$

where

G(18) = stand transpiration,
B(10) = ground surface area,
10 = conversion factor from $cm^3\ h^{-1}$ to mm h^{-1}.

This calculates transpiration in simple water dep equivalence, as is routinely used in hydrology literatur

SPECIAL FUNCTIONS

Special Function S1—Frost k_l Function

```
Function S1(TAIR, XHOUR, COND)
    IF(XHOUR – 5.0) 91, 90, 91
90  SRT = TAIR
91  IF(SRT . GT . 0.0) GO TO 92
    S1 = AMAX1(COND + 0.02 · SRT, 0.005)
    IF(SRT . LT . – 7.0) S1 = 0.005
    GO TO 93
92  S1 = COND + COND · 0.003 · (TAIR – 10.0)
93  RETURN
    END
```

The effect of air temperature on k_l is calculated Function S1 and called by G(15). The temperature effe has two sections. When air temperature is above 10° k_l is increased modestly (0.003 cm s^{-1} $°C^{-1}$), if belo 10° C, k_l is decreased by the same coefficient (Hinckl et al. 1978). There is evidence that subfreezing nig temperatures retard stomatal opening even after te perature recovery (Neilson and Jarvis 1976, Fahey 197

Kaufmann 1982); therefore, the other part of Function 1 determines if frost occurred at dawn, defined as 500 hours (SRT). If it had frozen, a much stronger k_l eduction is used (0.02 cm s^{-1} $°C^{-1}$) until 0500 the next norning.

pecial Function S3—Absolute Humidity Deficit

```
Function S3 (TA, RH)
ESD  = 6.1078 · EXP((17.269 · TA)/(237.3 + TA))
ES   = RH/100 · ESD
VPD  = AMAX1((ESD – ES), 0.0)
S3   = 217.0 E –6 · VPD/(TA + 273.16)
RETURN
END
```

If the evaporating surface of a leaf is assumed to be at aturation and leaf temperature to equal air tempera- ure, the evaporative demand in mass units can be ob- ained by first calculating saturation vapor pressure at 'AIR using the equation of Murray (1967). Then calcu- ate ambient vapor pressure (ES) using input relative umidity (RH). Vapor pressure deficit is defined as (ESD ES). Absolute humidity deficity (ABSHD) in grams per ubic centimeter is then calculated from VPD and TA nd returned to G(1) as S3. This function can be modified asily to calculate ABSHD from dewpoint or wetbulb epression instead of relative humidity.

DAYTRANS

The primary purpose of DAYTRANS is to develop a nore simplified, less data-intensive model that retains as nuch of the prediction accuracy of H2OTRANS as possi- le. A major simplification was going to a daily timestep n DAYTRANS. As a result, computer execution cost is lso greatly reduced. The overall structure and perspec- ve of the models are similar. DAYTRANS was written fter completion of H2OTRANS by removing the less crit- cal sections of H2OTRANS. Because much of the docu- nentation of DAYTRANS duplicates H2OTRANS, discus- ion here will concentrate on the differences between the nodels. Readers can refer to the comprehensive H2OTRANS section for documentation of the sections hat are basically identical. See figure 2 for the DAYTRANS compartment flow diagram.

TATE VARIABLES—X(i)

A list of state variables follows. See definitions for the omparable state variables in the H2OTRANS section.

		Unit
X(1)	= snowpack water content	cm^3
X(2)	= root zone soil water content	cm^3
X(3)	= tree sapwood water content	cm^3
X(4)	= transpiration (unlimited capacity)	cm^3
X(5)	= surface runoff (unlimited capacity)	cm^3
X(6)	= subsurface outflow (unlimited capacity)	cm^3
X(7)	= evaporation (unlimited capacity)	cm^3

FLOW FUNCTIONS—F(i,j)

A list of flow functions follows. See F(i,j) section in H2OTRANS for explanations.

F(1,2) = snowmelt input, G(50)
F(2,2) = precipitation input, G(1)
F(2,3) = root water uptake, G(53)
F(2,5) = surface runoff, G(51)
F(2,6) = subsurface outflow, G(52)
F(3,4) = transpiration, G(19)
F(7,7) = evaporation, canopy and litter, G(9)

DRIVING VARIABLES—Z(i)

DAYTRANS uses the following driving variables.

		Unit
Z(1)	= Julian date	day
Z(2)	= precipitation	cm
Z(3)	= air temperature (daylight average)	°C
Z(4)	= absolute humidity deficit (daylight average)	g cm^{-3}
Z(5)	= soil temperature, 20 cm	°C
Z(6)	= incoming shortwave radiation (daylight average)	ly min^{-1}
Z(7)	= daylength (sunrise-sunset)	s
Z(8)	= night minimum air temperature	°C

A primary reason for using DAYTRANS occurs when only daily meteorological data is available. It became evident executing both models that a critical factor in the success of the DAYTRANS simulation was the accuracy with which the climatic variables were averaged. As more meteorological stations record on microprocessor data-loggers, daily averages can be generated by electronic integration of the variable inputs throughout the day. Some suggestions on averaging certain daily meteorological data for use in DAYTRANS are presented next. Note that Z(3), Z(4), and Z(6) must be averaged for the daylight period only. This is based on the assumption that transpiration and water stress development occur only during the day.

Air Temperature—Z(3)

Frequently, only maximum and minimum air temperatures are recorded for a day. If the daylight course of air temperature is assumed to approximate three quadrants of a sine function (Parton and Logan 1981) as shown in figure 10, a simple approximation of daylight average air temperature can be derived.
The arithmetic mean is:

$$\bar{T} = (T_{max} + T_{min})/2 = \sin 0.$$

But integrating the sine function yields

$$\frac{1}{PI - (-PI/2)} \int_{-PI/2}^{PI} \sin \times dx = 0.212$$

where
PI = 3.1416.

So

$$T_{ave} = 0.212(T_{max} - \bar{T}) + \bar{T}$$

where

T_{ave} = average daylight air temperature,
$\bar{T}$ = arithmetic mean of T_{max} and T_{min}.

This equation was used to generate a DAYTRANS data file that was compared against a data file developed from averaging recorded hourly air temperature values. The regression of hourly averaged air temperature daylight averages against the sine function weighted daylight averages was:

$$T_{ha} = -1.14 + 1.12\ T_{sf} \quad R^2 = 0.93\ n = 120\ days$$

where

T_{ha} = air temperature, hourly averaged,
T_{sf} = air temperature, weighted sine function.

The same regression against arithmetic maximum-minimum averages was

$$T_{ha} = 0.74 + 1.20\ T_{mm} \quad R^2 = 0.88\ n = 120\ days$$

where

T_{mm} = maximum-minimum averaged temperatures.

The sine function-weighted average more closely approaches the optimum $T_{ave} = T_{ha}$ prediction, as shown by a comparison of Y-intercepts, slopes and correlation coefficients.

It should be emphasized that these data manipulations are done in developing the DAYTRANS input data file. This is not done internally by the DAYTRANS program, although it could be if a permanent data base required it.

Absolute Humidity Deficit—Z(4)

Absolute humidity deficit is calculated for Z(4) by reading in TAIR, air temperature, and XRHUM (relative humidity). Four equations are then used to calculate saturation vapor pressure, absolute humidity, and absolute humidity deficit. These equations are covered in Special Function S3 in H2OTRANS. Some considerations for estimating daily average relative humidity follow.

The diurnal course of relative humidity often is a mirror image of the air temperature trace because of the influence of air temperature on saturation vapor pressure. Consequently, a sine function-weighted correction was also done for humidity daily averages. The analysis was similar to that in figure 10, except that the Y-axis was reversed.

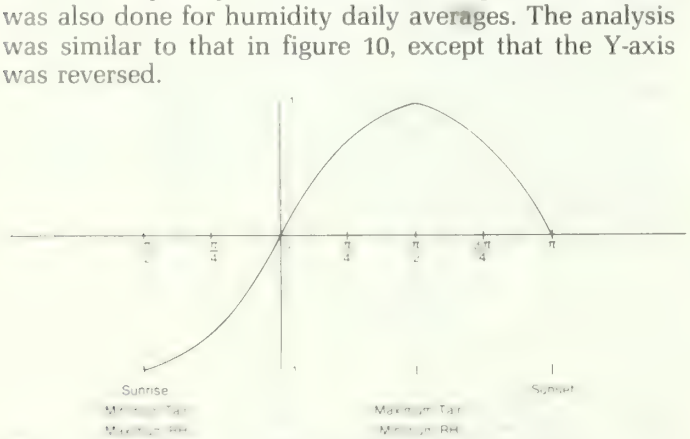


Figure 10.—A diagram analyzing the use of a sine function to approximate average air temperature and relative humidity during daylight hours, given only maximum and minimum values.

$$RH_{ave} = \bar{R}\bar{H} - 0.212\ (\bar{R}\bar{H} - RH_{min}).$$

The regression between hourly averaged RH and t sine function-weighted daily RH was

$$RH_{ave} = -17.0 + 1.32\ RH_{sf} \quad R^2 = 0.84\ n = 120\ days$$

This corrected RH was also an improvement over daily RH produced merely by averaging the maximu and minimum RH.

Again, it should be stated that these data reductio must be done outside of the main DAYTRANS progra Also, this sine function approximated diurnal humidi curve would not be appropriate when using an absolu measure of atmospheric water vapor such as dewpoin

Soil Temperature—Z(5)

Because the diurnal temperature variation at 20-c depth is usually less than 1° C, any midday soil temper ture measurement is an adequate daily average for t purposes of this model.

Incoming Shortwave Radiation—Z(6)

If total daily radiation is collected, radiation divide by day length in minutes will provide the daily avera used in Z(6). Day length for a flat surface is computed Z(7).

In the absence of any radiation data, daily potenti radiation can be determined (Garnier and Ohmura 196 Swift 1976). Assuming a sine wave approximation of cloudless diurnal radiation trace, peak daily radiatio times 0.7 provides a fair approximation of daily avera incoming radiation for relatively clear areas.

Day Length—Z(7)

```
XD    = JD - 79
IF(XD . LT . 0.0) XD = 286.0 + JD
DAY   = 3.125·(SIN(XD·0.01721)) + 12.0
Z(7)  = DAY · 3600 · 0.8
```

This sine function, driven by Julian date (JD), co putes day length in hours (DAY), at 41° N. latitude, for flat surface, on any day of the year. Because this da length calculation overestimates the duration of daylig with sufficient intensity to open stomata (0.1 ly min^{-1} analysis of diurnal radiation traces showed that a 0. correction more closely approximates the length of e fective daylight for transpiration. The sine equation ca be adjusted for any latitude by the 3.125 coefficient (3. for 45° N.) and is typically accurate to within 15 minute per day. More complex equations correcting for diffe ent slopes and aspects are also available (Garnier an Ohmura 1968, Swift 1976).

AUXILIARY CONSTANTS—B(i)

		Unit
B(1)	= maximum soil surface infiltration rate	cm day^{-1}
B(2)	= root zone soil capacity	cm^3
B(3)	= tree sapwood storage capacity	cm^3

B(4) = tree or stand leaf area cm^2
B(5) = maximum canopy leaf conductance, k_l $cm\ s^{-1}$
B(6) = canopy and litter interception coefficient cm
B(7) = ground surface area cm^2
B(8) = snowmelt coefficient $cm\ °C^{-1}$
B(9) = midcrown tree height m
B(10) = spring minimum predawn ψ_l MPa
B(11) = stomatal closure threshold MPa

INTERMEDIATE VARIABLES—G(i)

G(1) = effective precipitation ($cm^3\ day^{-1}$)

$$G(1) = AMAX1((Z(2)–(B(4)/B(7)) \cdot B(6)) \cdot B(7), 0.0)$$

where
Z(2) = precipitation,
B(4) = stand leaf area,
B(6) = canopy and litter interception coefficient,
B(7) = ground surface area.

This equation reads input precipitation, Z(2), subtracts canopy and litter interception, B(6), as a function of leaf area index, B(4)/B(7), and multiplies by ground surface area, B(7), to give volume of water input. See G(50) in H2OTRANS.

G(2) = available water fraction, root zone ($cm^3\ cm^{-3}$)

$$G(2) = X(2)/B(2)$$

where
X(2) = current root zone water storage,
B(2) = root zone water capacity.

G(3) = available water fraction, sapwood ($cm^3\ cm^{-3}$)

$$G(3) = X(3)/B(3)$$

where
X(3) = current sapwood water storage,
B(3) = sapwood storage capacity.

G(4) = snowmelt ($cm^3\ day^{-1}$)

$$G(4) = AMAX1(B(8) \cdot Z(3) \cdot B(7), 0.0)$$
$$IF\ (X(1)\ .LE.\ 0.0)\ G(4) = 0.0$$

where
B(8) = snowmelt coefficient,
Z(3) = air temperature,
B(7) = ground surface area,
X(1) = current snowpack water content.

This equation melts the snowpack, X(1) at a rate B(8), based on average day air temperature, Z(3), multiplied by ground surface area, B(7), and gives the volume of water melted. See G(51) in H2OTRANS.

G(5) = leaf area index ($cm^2\ cm^{-2}$)

$$G(5) = B(4)/B(7)$$

where
B(4) = stand leaf area,
B(7) = ground surface area.

G(9) = canopy and litter evaporation ($cm^3\ day^{-1}$)

$$G(9) = Z(2) \cdot B(7) – G(1)$$

where
Z(2) = precipitation,
B(7) = ground surface area,
G(1) = effective precipitation into the soil.

Evaporation of water from canopy and litter interception is calculated by G(9).

G(10) = predawn leaf water potential, $B\psi_l$ (–MPa)

$$G(10) = AMAX1(B(10), 0.2/G(2) + 0.01 \cdot B(9), 0.0)$$

where
B(10) = spring minimum predawn ψ_l,
0.2 = curve-fitting coefficient,
G(2) = available water fraction, root zone,
0.01 = hydrostatic gradient constant ($MPa\ m^{-1}$),
B(9) = midcrown tree height.

Pre-dawn leaf water potential is predicted from available soil moisture G(2), and is corrected for tree height. See G(10) in H2OTRANS.

G(12) = light-saturated leaf area index ($m^2\ m^{-2}$)

$$G(12) = 10.0 \cdot (1.0–EXP(–4.6 \cdot Z(6)))$$

where
10.0, 1.0, –4.6 = curve-fitting coefficients,
Z(6) = incoming shortwave radiation.

This equation computes the amount of leaf area index that would be receiving at least 10% of full sunlight at the measured radiation intensity, Z(6), and assumed vertical attenuation. See G(11) in H2OTRANS.

G(13) = radiation-induced k_l limiting fraction (dim.)

$$G(13) = 1.0–((G(5)–G(12))/G(5))$$
$$IF(G(12)\ .GT.\ G(5))\ G(13) = 1.0$$

where
G(5) = leaf area index,
G(12) = light-saturated leaf area index.

Canopy leaf conductance is reduced by G(13), the fraction of the canopy receiving insufficient radiation to open stomata. See G(12) in H2OTRANS.

G(14) = k_l, predawn leaf water potential correction ($cm\ s^{-1}$)

$$G(14) = B(5) – (B(5)/B(11)–B(10)) \cdot (G(10)–B(10))$$
$$IF(G(10)\ .GE.\ B(11))\ G(14) = 0.005$$

where
B(5) = maximum canopy k_l,
B(5)/B(11)–B(10) = the slope of the k_l reduction calculated by the range of k_l (maximum (B(5)) to 0) divided by the corresponding range of ψ_l (spring minimum ψ_l, B(10) to stomatal closure point, B(11)).
G(10) = predawn leaf water potential,
B(10) = spring minimum ψ_l,
0.005 = minimum k_l, stomatal closure.

This important function relates reduction in canopy k_l to soil moisture deficits through the predawn leaf water potential function, G(10). See the discussion in H2OTRANS for G(13).

G(15) = k_l, humidity correction (cm s^{-1})

$$G(15) = G(14)–(G(14)\cdot 0.05\cdot(Z(4)\cdot 10^{6}–4.0))$$
$$IF(G(15) .LE. 0.0)\ G(15) = 0.005$$

where
- G(14) = k_l, leaf water potential effects,
- 0.05 = slope of k_l reduction,
- Z(4) = absolute humidity deficit,
- 10^6 = unit scalar,
- 4.0 = humidity control threshold factor,
- 0.005 = stomatal closure constant.

This function produces the humidity effects on k_l analagous to G(14) in H2OTRANS.

G(16) = k_l, air temperature correction (cm s^{-1})

$$G(16) = G(15) + G(15)\cdot 0.003\cdot(Z(3)–10.0)$$
$$IF(Z(8) .LT. 0.0)\ G(16) = AMAX1(G(15) + 0.02\cdot Z(8), 0.005)$$

where
- G(15) = k_l, humidity effects,
- 0.02, 0.003 = slope of k_l reduction (cm s^{-1} °C^{-1}),
- Z(3) = air temperature,
- 10.0 = temperature reduction threshold,
- Z(8) = night minimum air temperature,
- 0.005 = k_l at stomatal closure.

These equations increase k_l slightly with air temperatures above 10° C, reduce k_l at temperatures between 0° and 10°, and markedly reduce k_l at night minimum temperatures below 0.0°. See special function S1, H2OTRANS.

G(17) = k_l, final canopy average (cm s^{-1})

$$G(17) = G(16)\cdot G(13)$$

where
- G(16) = k_l, plus humidity, air temperature and leaf water potential controls,
- G(13) = k_l, radiation reduction fraction,

See G(17) in H2OTRANS.

G(18) = transpiration flux density (g cm^{-2} s^{-1})

$$G(18) = Z(4)\cdot G(17)$$

where
- Z(4) = absolute humidity deficit,
- G(17) = k_l, final canopy average,

See G(17) in H2OTRANS.

G(19) = daily stand transpiration (g day^{-1})

$$G(19) = G(18)\cdot B(4)\cdot Z(7)$$

where
- G(18) = transpiration flux density,
- B(4) = stand leaf area,
- Z(7) = day length,

Final stand transpiration G(19) = F(3,4).

G(20) = transpiration/potential transpiration ratio (dim.)

$$G(20 = G(17)/B(5)$$

where
- G(17) = k_l, final canopy average,
- B(5) = maximum k_l,

See G(76) in H2OTRANS.

G(21) = areal transpiration (mm day^{-1})

$$G(21) = G(19)/B(7)\cdot 10.0$$

where
- G(19) = daily stand transpiration,
- B(7) = ground surface area.

G(50) = precipitation and snowmelt water input (cm day^{-1})

$$G(50) = G(4)$$
$$IF\ (X(1)–G(4)\ .LT.\ 0.0)\ G(50) = X(1)$$

where
- G(4) = snowmelt,
- X(1) = snowpack water content.

Water input into X(2) comes from precipitation and snowmelt. Snowmelt, G(4), cannot exceed the current snowpack water content, X(1). G(50) equals F(1,2).

G(51) = surface runoff (cm^3 day^{-1})

$$G(51) = 0.0$$
$$IF\ ((G(1)+G(4))/B(7)\ .GT.\ B(1))\ G(51) = (G(50)–B(1))\cdot B(7)$$

where
- G(1) = precipitation,
- G(4) = snowmelt,
- B(7) = ground surface area,
- B(1) = maximum soil surface infiltration rate,
- G(50) = precipitation and snowmelt water input.

Water input in excess of the maximum soil surface infiltration rate is routed to surface runoff. G(51) equals F(2,5).

G(52) = subsurface outflow (cm^3 day^{-1})

$$G(52) = 0.0$$
$$IF\ (X(2)+G(50)\ .GT.\ B(2))\ G(52) = X(2)+G(50)–G(51)–B(2$$

where
- X(2) = current root zone soil water content
- G(50) = precipitation and snowmelt water input,
- G(51) = surface runoff,
- B(2) = root zone soil water capacity.

If water input, G(50), minus surface runoff exceeds the capacity of X(2), the excess water goes to subsurface outflow. G(52) equals F(2,6).

G(53) = root water uptake (cm^3 day^{-1})

$$G(53) = B(3)–X(3)+G(19)$$

where
- B(3) = tree sapwood storage capacity,
- X(3) = current sapwood water storage,
- G(19) = daily transpiration.

This equation computes water transfer from X(2) to X(3) based solely on deficits in X(3) and transpiration demand. In a previous model version, I had a soil-water uptake resistance also controlling water movement at this point, but it seems to be unnecessary.

The feedback resistance produced by the effects of soil water deficit on predawn leaf water potential G(10), leaf conductance, G(13), and transpiration, G(19), controls the overwithdrawal of water from X(2) excep

ter extreme, extended water stress. At that point the odel should predict tree mortality!

Two additional capabilities were recently added to AYTRANS, although they were not included in the sults section.

Penman-Monteith calculation of transpiration

```
      FUNCTION PENMON(TAIR,RAD,VPD,XLAI,COND)
      GAMMA = 0.646 + 0.0006*TAIR
      PLAI = XLAI/2.
      T1 = TAIR + 0.5
      T2 = TAIR–0.5
      SVP1 = 6.1078*EXP((17.269*T1)/(237.0 + T1))
      SVP2 = 6.1078*EXP((17.269*T2)/(237.0 + T2))
      SLOPE = SVP1–SVP2
      XNETR = RAD*0.8*697.3
      CP = 1.01E + 3
      PA = 1.292–0.00428*TAIR
      RA = 5.0
      RS = 100./COND
      XLAT = (2.501 – 0.0024*TAIR) * 1.0E + 6
      XTRANS = ((SLOPE*XNETR)/PLAI
     C+(CP*PA)*(VPD/RA))/
     C (SLOPE + GAMMA*(1.0 + RS/RA))
      PENMON = XTRANS/(XLAT * 10.)
      RETURN
      END
```

This is an adaptation of the widely used Penman-onteith equation (Jarvis et al. 1976):

$$\lambda E = \frac{(\Delta R\eta/PLAI) + C_p P(VPD)/r_a}{\Delta + \gamma (1 + r_s/r_a)}$$

here

- λ = XLAT = latent heat of vaporization of water (J kg^{-1}),
- E = XTRANS = evaporation (W m^{-2}),
- PENMON = evaporation (g cm^{-2} s^{-1}),
- Δ = SLOPE = slope of the saturation vapor pressure curve at T_{air}, (mbar $°C^{-1}$),
- $R\eta$ = XNETR = net radiation (W m^{-2}),
- PLAI = projected leaf area index,
- C_p = CP = specific heat of air (J kg^{-1} $°C^{-1}$),
- P = PA = density of air (Kg m^{-3}),
- VPD = vapor pressure deficit (mb),
- r_a = RA = aerodynamic resistance (s m^{-1}),
- γ = GAMMA = psychrometric constant (mb $°C^{-1}$), calculated by $\gamma = C_pP/\lambda$,
- r_s = RS = stomatal resistance, calculated as $1/k_l$ G(17), (s m^{-1})).

Under conditions of high net radiation but low air mperature common in spring, radiant energy becomes significant driving variable for evaporation. This uation assumes a constant r_a of 5.0 s m^{-1} with no indspeed input. It also divides the net radiation term projected leaf area index to more realistically ex-ess the radiant energy loading on different canopy yers. This calculation of stand transpiration can be bstituted for G(17) in H2OTRANS or G(18) in AYTRANS.

2. Net photosynthesis subroutine

```
      SUBROUTINE PHOTO
      COMMON K,X(2,20),F(20,20),G(100),
     B(100),Z(20),Y(160)
C
C  Z(10) = CANOPY AVERAGE RADIATION
C
      Z(10) = (Z(6) + Z(6)*EXP(–0.7*G(5)/2.))/2.
C
C  Z(9) = AVERAGE NIGHT TEMPERATURE
C
      Z(9) = (Z(3) + Z(8))/2.
C
      G(64) = ((Z(10)-0.0143)/(Z(10) + 0.322))*
C     (0.0182 + 0.0105*Z(3)–0.000194*(Z(3)**2))
      IF(G(64).LT.0.)G(64) = 0.
      G(65) = (0.0006*(G(17)/1.6)*G(64))/
C     ((G(17)/1.6) + G(64))
      G(62) = 0.001*(24.-Z(7)/3600.)*EXP(0.2*Z(9))
      G(66) = G(65)*Z(7)
      G(67) = G(66)–G(62)
      RETURN
      END
```

This subroutine was derived from the photosynthesis model of Lohammar et al. (1980).

G(65) = PSN = gross photosynthesis (mg cm^{-2} s^{-1})

$$G(65) = PSN = \frac{\Delta CO_2 (k_l \cdot g_m)}{k_l + g_m}$$

where

- ΔCO_2 = CO_2 gradient from the atmosphere to the carboxylation site in the leaf (≅0), taken as 0.0006 kg m^{-3}
- k_l = G(17) = leaf conductance to water vapor (cm s^{-1}),
- 1.6 = ratio of the diffusion coefficients of water vapor and CO_2 in the air,
- g_m = G(64) = mesophyll CO_2 conductance (cm s^{-1}).

G(64) is calculated by Lohammar et al. (1980) as:

$$G(64) = g_m = \frac{I - I_o}{I + I_{1/2}} \cdot \alpha f(T)$$

where

- I = Z(10) = incoming shortwave radiation (W m^{-2}) with a conversion factor of 1 W m^{-2} = 1.43 × 10^{-3} cal cm^{-2} min^{-1},
- I_o = light compensation point, where net PSN = 0, given as 10 W m^{-2} = 0.0143 cal cm^{-2} min^{-1},
- $I_{1/2}$ = the irradiance at which g_m is half of its maximum value, given as 225 W m^{-2} = –0.322 cal cm^{-2} min^{-1},
- α f(T) = the maximum g_m at any air temperature T, generated by the polynomial equation:

$$\alpha = 0.0182 + 0.0105 (Z(3)) + 0.000194 (Z(3)^2)$$

This curve was fitted to data from Nielson and Jarvis (1976), R^2 = 0.67, and checked against a variety of other sources for conifers. It calculates a maximum g_m = 0.16 cm s^{-1} at 26.3° C.

G(66) = Daily net CO_2 uptake (mg cm^{-2})

$$G(66) = G(65) \cdot Z(7)$$

where

G(65) = gross photosynthesis (mg cm^{-2} s^{-1}),
Z(7) = daylength (s).

G(62) = Night foliar respiration loss (mg cm^{-2}

$$G(62) = 0.001 \cdot (24 - (Z(7)/3600)) \cdot \exp(0.2 \cdot Z(9))$$

where

24 – (Z(7)/3600) = night length (h),
Z(9) = average night air temperature (°C).

This equation was used by Emmingham and Waring (1977).

Finally, 24-hour net photosynthesis is approximated by

G(67) = 24-hour net CO_2 uptake (mg cm^{-2})

$$G(67) = G(66) - G(62)$$

where

G(66) = daily net CO_2 uptake,
G(62) = night foliar respiration loss.

RESULTS

This preliminary validation had two objectives. First was to test if H2OTRANS and DAYTRANS were capable of simulating the diurnal and seasonal patterns of transpiration and water stress development in lodgepole pine. Because transpiration of a stand cannot be measured directly, validation focused on diurnal and seasonal patterns of measurable variables ψ_l and k_l in individual trees and soil moisture depletion. The second objective was to determine if the much smaller, simplified DAYTRANS model could predict seasonal patterns with minimal resolution loss compared to H2OTRANS. The H2OTRANS model was designed as a research tool and requires more detailed climatic data and specialized parameter estimates. DAYTRANS was an attempt to scale the logic of the H2OTRANS model down to a level where input data requirements would be feasible for operational use.

FIELD VALIDATION SITE

During the fall of 1977, a study site was established at the USDA Forest Service Fraser Experimental Forest in the central Colorado Rocky Mountains. The site studied supported an uneven-aged *Pinus contorta* stand, with occasional *Populus tremuloides*, ranging in age from 10 years to the 12-m tall canopy dominants at 60 years. The elevation was 2,700 m, and topography level on a glacial outwash. Stand density was 2,740 trees per hectare with a basal area of 30.7 m^2 ha^{-1} and site index of 22.6 m at 100 years.

The climate of this area is cool and dry for coniferous forests. Temperature extremes of from –40° C to 32° C have been recorded. Frost is possible on any night during the growing season. Minimum temperatures on s during the summer of 1978 were always below 4° C, a maximum daily air temperatures averaged from 20° C 23° C, with a high of 26° C. Midday relative humid typically ranged from 15% to 25%, except during th derstorms. Precipitation averages 58.4 cm per ye with nearly two-thirds falling as snow between Octob and May (Alexander and Watkins 1977).

Beginning on Julian date 130 (May 10), 1978, co tinuous meteorological data was recorded until JD 2 (September 10), 1978. Air temperature measured by thermistor was continuously recorded by strip cha Dewpoint temperature was measured with a heated li ium chloride dew point sensor, also recorded contin ously on the strip chart. These instruments we mounted in a standard, vented weather station b placed 1.5 m above the ground. Onsite soil temperatu at 15-cm depth was taken with a dial temperature pro once a day. Also, a sling psychrometer was used eve two hours during daylight hours to take wet- and d bulb temperatures for backup measurement of air te perature and humidity. Precipitation and a continuo trace of incoming shortwave radiation were bei recorded 5 km away at the Fraser Experimental For headquarters. At the end of the summer, these da were compiled into the format required for input in H2OTRANS and DAYTRANS as Z, or driving, variable

PARAMETER ESTIMATES

To run the models, a number of site and sta parameters were also needed. Because a complete b mass survey of the stand could not be done and valid tion was focusing on individual tree responses, a sing tree representative of the stand was defined for mod ing. The characteristics of this tree follow:

Ground surface area = 3.5 m^2
Diameter (b.h.) = 8.2 cm
Height = 7.0 m
Needle weight = 2.87 kg
Needle area = 2.1×10^5 cm^2
LAI = 6.0
Sapwood basal area = 73.9 cm^2
Sapwood volume = 21,000 cm^3.

Trees of this general size had been used to gather da for some of the physiological responses in the mod Consequently, these parameter estimates can verified from measured biomass data (Running 1980 Also, the "observed" field data used in this prelimina validation were taken on trees of this size.

A list of initial conditions for the X(i), state variable at the beginning of the H2OTRANS and DAYTRA model runs on JD 130, 1978, and the B(i), consta parameters, is given in table 1.

VALIDATION RUNS

Simulation runs were made for JD 130 to 245, 1978, H2OTRANS and DAYTRANS. The overall water budge predicted by the two models were:

	H2OTRANS	DAYTRANS
Transpiration	36%	38%
Evaporation	15%	17%
Subsurface outflow	49%	45%
Total	42.9 cm	

This was taken from a total water supply during the period consisting of snowpack, soil water, and precipitation. Figure 11 plots the seasonal progression of transpiration and soil moisture depletion simulated by the models, and the actual soil moisture depletion measured on site by technicians using a neutron probe. The neutron probe data, taken at monthly intervals, from 0 to 1.5 m depth, at 15-cm increments, from four access tubes, is shown in Running (1980a). The initiation of soil moisture depletion and final magnitude of drawdown were predicted fairly accurately by both models. The models appear to overestimate water depletion rates somewhat during midsummer; however, the slope of overall seasonal depletion was fairly closely represented. DAYTRANS predicted transpiration rates roughly 5% higher than H2OTRANS during midsummer beginning around JD 170. This discrepancy is attributed to the difficulties of averaging evaporative demand accurately for the day and scaling the humidity reduction of k_l correctly in DAYTRANS to averaged values. Final seasonal transpiration estimates agree to within 4%, which is remarkable considering the much reduced resolution of DAYTRANS.

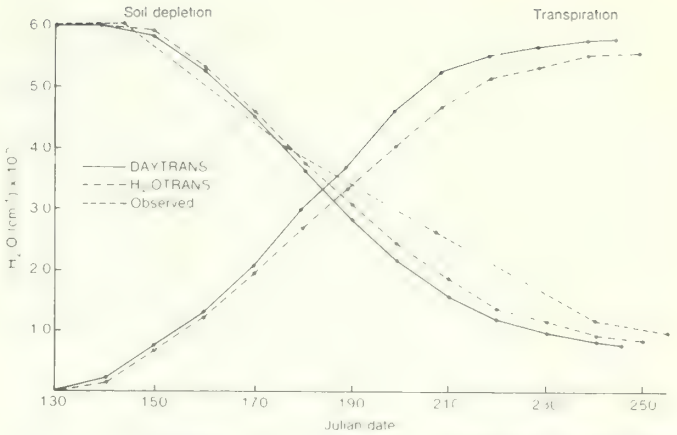


Figure 11.—Simulation runs comparing H2OTRANS and DAYTRANS results to observed data on lodgepole pine at the Fraser Experimental Forest study site during the summer of 1978. Soil water depletion was measured by a neutron probe. There is no observed data for transpiration; therefore, only the comparison of model predictions is shown.

Predawn leaf water potential, $B\psi_l$, is considered by many tree physiologists to be the best and most easily measured way of assessing seasonal water stress development in a tree. In figure 12, the H2OTRANS and DAYTRANS predictions of seasonal stress development $B\psi_l$ are shown compared to a compilation of observed $B\psi_l$ measurements taken at different lodgepole pine trees at the Fraser site throughout the summer of 1978. Again, both models performed well relative to each other and the measured field data.

Table 1.—Model conditions for the preliminary validation exercise

H2OTRANS		DAYTRANS	
X(i): Initial conditions (cm^3)		X(i): Initial conditions (cm^3)	
X(1) = 7.2×10^5		X(1) = 7.2×10^5	
X(2) = 0.0		X(2) = 6.0×10^5	
X(3) = 1.0×10^4		X(3) = 1.33×10^4	
X(4) = 3.0×10^5		X(4) = 0.0	
X(5) = 3.0×10^5		X(5) = 0.0	
X(6) = 0.0		X(6) = 0.0	
X(7) = 1.6×10^3		X(7) = 0.0	
X(8) = 0.9×10^2			
X(9) = 0.0			
X(10) = 0.0			
B(i) Constant parameters		B(i): Constant parameters	
B(1) = 0.015	$cm\ h^{-1}\ °C^{-1}$	B(1) = 5.0×10^1	$cm\ day^{-1}$
B(2) = 10.0	$cm\ h^{-1}$	B(2) = 6.0×10^5	cm^3
B(3) = 3.5×10^4	cm^3	B(3) = 1.33×10^4	cm^3
B(4) = 3.0×10^5	cm^3	B(4) = 2.1×10^5	cm^2
B(5) = 3.0×10^5	cm^3	B(5) = 0.15	$cm\ s^{-1}$
B(6) = 0.010	$cm\ LAI^{-1}\ h^{-1}$	B(6) = 0.30	cm LAI ^{1}
B(7) = 1.6×10^4	cm^3	B(7) = 3.5×10^4	cm^2
B(8) = 9.0×10^2	cm^3	B(8) = 0.15	$cm\ °C^{-1}$
B(9) = 2.1×10^5	cm^2	B(9) = 7.0	m
B(10) = 3.5×10^4	cm^2	B(10) = 0.4	MPa
B(11) = 7.0	m	B(11) = 1.5	MPa
B(12) = 0.15	$cm\ s^{-1}$		
B(13) = 0.4	MPa		
B(14) = 1.5	MPa		
B(15) = 74.0	cm^2		
B(16) = 2.0	h^{-1}		
B(17) = 20.0	h^{-1}		

Leaf conductance is the most easily measured physiological variable that is closely related to transpiration. To evaluate the model's predictions of k_l, the seasonal progression of maximum daily k_l was plotted in figure 13 and compared to observed k_l data compiled from measurements on different lodgepole pine taken throughout the summer of 1978. The beginning of stress development around JD 185 is evident in figure 12, with corresponding reducing of k_l in figure 13. Note that in both figures 12 and 13 the models are relatively successful in predicting (1) the time of initial stress development, and (2) the overall rate of increase in stress (fig. 12) and reduction in k_l (fig. 13).

To further examine the ability of H2OTRANS to simulate diurnal dynamics of ψ_l and k_l, 19 days of ψ_l and k_l data from 12 different trees at the Fraser site were compiled. Each data point, representing a specific date and time of day, was plotted against the corresponding H2OTRANS simulated value for that date and time. The results of this analysis, shown in figure 14 for ψ_l and figure 15 for k_l, cover an extensive array of conditions of temperature, humidity, radiation, and soil moisture expected in measurements taken from sunrise to sunset throughout the summer. Both the slope and Y-intercept of the linear regression equation in figure 14 correspond well with the optimal 1:1 where every measured value is predicted exactly. It is evident in analyzing the scatter of points that the model tends to underestimate ψ_l in the 1.0-1.3 MPa range and overestimate ψ_l in the 1.3-1.5 MPa range.

The diurnal prediction of k_l was less successful, possibly because of the large number of factors controlling k_l. The Y-intercept of the regression line shows that at low k_l values (below 0.06 cm s^{-1}) H2OTRANS often overestimates k_l. At k_l values above 0.08 cm s^{-1} the model underestimates k_l. This illustrates the concept that when average "conservative" response equations are used in a model, the deviations from the average will be most noticeable at the extremes of the response curves. Fortunately, these high resolution errors compensated each other, allowing reasonable estimates of the longer term seasonal trends of tree water use and stress development.

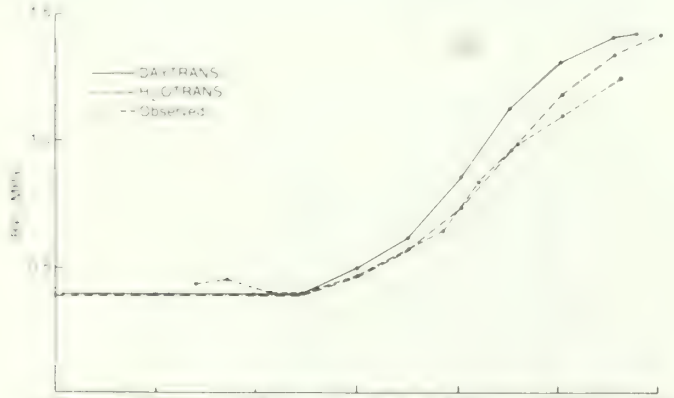


Figure 12.—A comparison of H2OTRANS and DAYTRANS predictions of increase in tree water stress (predawn leaf water potential, $B\psi_l$) with measured values on lodgepole pine at the Fraser Experimental Forest study site during the summer of 1978.

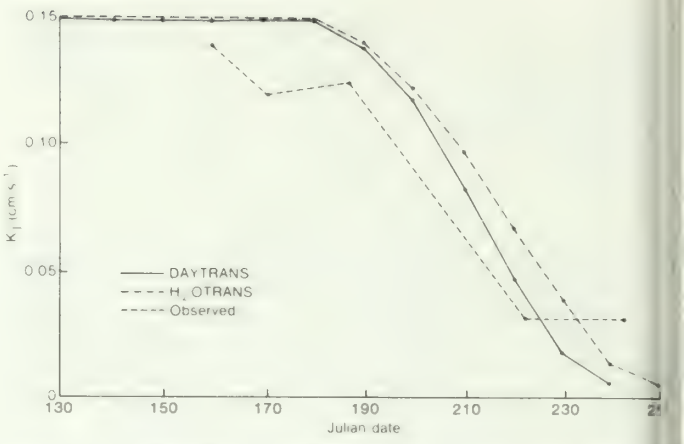


Figure 13.—Predicted and observed levels of maximum daily leaf conductance, k_l, on lodgepole pine at the Fraser site throughout the summer of 1978. Observed points represent an average of 9-11 diffusion porometer measurements taken throughout the tree crown.

SENSITIVITY ANALYSIS

To assess the response of the overall model to various "perturbations," a sensitivity analysis was run on DAYTRANS. A similar test was not run on H2OTRANS because the models are so similar and the cost and computer time of running the larger model was prohibitive. To execute this analysis, six independent variables were individually changed; first an increase of 50% then a decrease of 50%, for a total of 12 model runs. The variables changed were initial snowpack water, X(1), rooting zone water capacity, B(2), leaf area, B(4), maximum k_l, B(5), interception coefficient, B(6), and snowmelt coefficient, B(8). Three dependent variables were analyzed to determine changes brought about by these +/–50% perturbations. The dependent variables were total transpiration, X(4), total subsurface outflow, X(6), and predawn leaf water potential, G(10). The results of this sensitivity test are given in table 2.

Changes in the snowpack primarily caused changes in subsurface outflow. Snowmelt goes through the system relatively quickly in the spring; therefore, once the rooting zone soil is saturated, the water is gone before trees can use much. The rooting zone is the fundamental source of water for the tree. Consequently, changes in root zone water capacity had large effects on transpiration and tree water stress development. This is probably the most difficult parameter in the model to accurately define. Increasing leaf area made little difference or anything except causing higher water stress development, because the soil water was depleted sooner. Decreased leaf area markedly decreased transpiration and water stress and increased subsurface outflow somewhat.

Increased maximum k_l made surprisingly little difference to transpiration; water was used more quickly, but the overall available amount changed very little. This analysis does not reflect results that would be obtained from different sites. On a less water stressed site that retained substantial available soil water at the end of the summer, increased maximum k_l or increased leaf area would cause much higher transpiration.

Table 2.—A sensitivity analysis of DAYTRANS

Independent variables	Dependent variables: X(4) Transpiration	X(6) Subsurface outflow	G(10) Predawn leaf ψ
X(1): Snowpack water			
+50%	+2%	+50%	−3%
−50%	−4%	−49%	+4%
X(2): Root zone water			
+50%	+22%	0	−48%
−50%	−45%	0	+40%
X(4): Leaf area			
+50%	+6%	−2%	+25%
−50%	−36%	+7%	−63%
X(5): Maximum k_l			
+50%	+10%	−6%	+21%
−50%	−43%	+3%	−66%
X(6): Interception coeff.			
+50%	0	0	0
−50%	0	+5%	0
X(8): Snowmelt coeff.			
+50%	−2%	+2%	+2%
−50%	+7%	−7%	−10%

The results from the change in interception coefficients are rather artificial because virtually no rain fell during the summer of 1978. During preliminary model runs, it was found that changes in interception can radically change transpiration and water stress predictions. A very low interception rate can cause a small shower to recharge the soil, eliminating all water stress, while, in fact, it requires a rainfall event on the order of

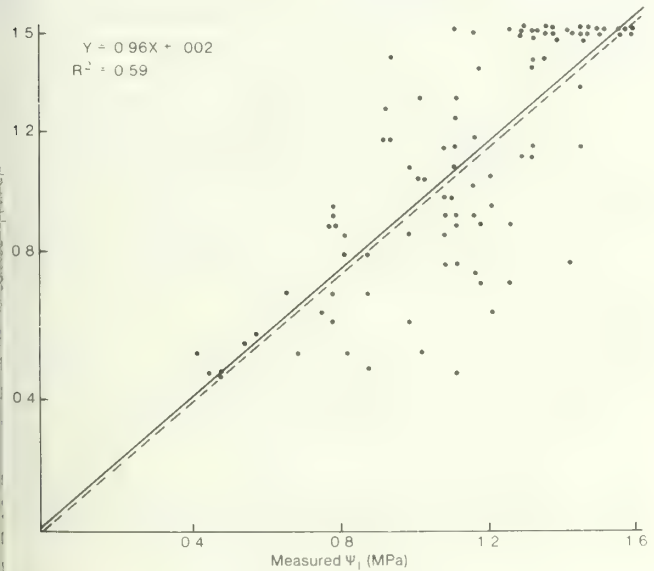


Figure 14.—A summary of all leaf water potentials, ψ_l, measured with a pressure chamber on lodgepole pine at the Fraser site during 1978 compared to predicted ψ_l from the H2OTRANS simulation run. The points represent data taken at all times of the day from sunrise to sunset. The dashed line shows the 1:1 ratio.

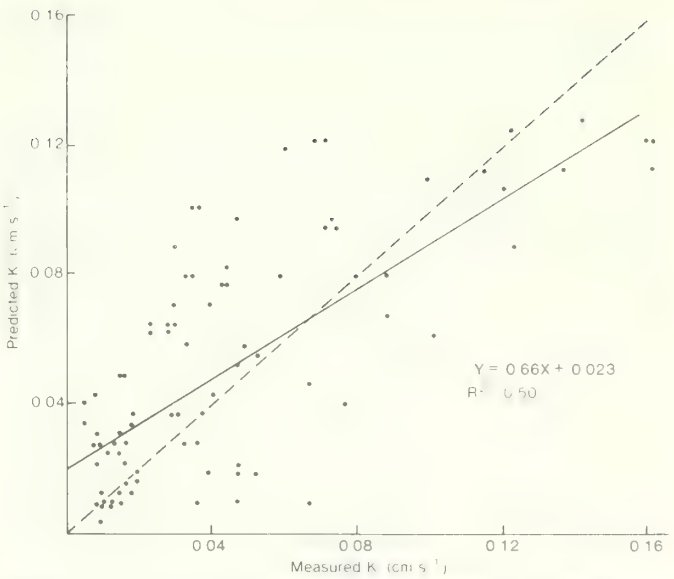


Figure 15.—A summary of all measured crown leaf conductance averages from lodgepole pine on the Fraser site, compared to predicted k_l from the 1978 H2OTRANS simulation run. Each measured point is the average of 9-11 diffusion porometer readings taken throughout the tree crown on foliage ranging from 0 to 3 years old. Sampling was done periodically from sunrise to sunset.

1.5 cm in 24 hours to cause substantial soil recharge in the Fraser stand.

The sensitivity of the snowmelt coefficient also appears to be low, but this could be misleading. A site with a larger snowpack would show higher sensitivity to the influence of the melt rate in partitioning snowmelt to transpiration versus subsurface outflow.

CONCLUSIONS

The preliminary validation of H2OTRANS and DAYTRANS demonstrates that the models are both capable of estimating reasonable water balances for lodgepole pine (fig. 11). The models also appear capable of estimating the physiology of seasonal water stress development in lodgepole pine (figs. 12 and 13). In particular, H2OTRANS is able to track measured ψ_l and k_l diurnally over a wide variety of conditions (figs. 14 and 15). Much of the models' emphasis is on the control of k_l by temperature, radiation, humidity and soil water supply.

The use of morning maximum leaf conductance as a starting point for diurnal k_l calculations seems valuable. The linkage of morning maximum k_l to soil water status through predawn leaf water potential gave fairly accurate results.

The calculation of ψ_l in H2OTRANS is unique and its success (fig. 15) can be attributed to two things. First, the flow resistance used to calculate ψ_l has both a soil temperature and soil moisture component. Second, the flow that generates ψ_l is the root water uptake, not the transpiration rate (which other models have used). This model configuration allows for capacitance in the tree hydraulic system and yields the ψ_l diurnal hysteresis that has been observed in the field by many researchers.

The generality of this ψ_l and k_l paradigm remains uncertain until it can be tested on other species under different conditions.

A primary conclusion from this work has been that prediction of tree water stress development requires more than just accurate physiological response functions. Of equal importance is sound representation of hydrologic inputs and storages. The system inputs and storages control the timing of when water stress begins in the trees. The physiological processes primarily control the subsequent rate of tree water stress development. Interception and surface evaporation losses must be accurate to determine effective precipitation input. Potential errors from these sources were minimized in this validation because the Fraser site had only 7.4 cm of precipitation during the entire summer of 1978. On wetter sites, these processes could profoundly influence the success of a simulation. Of equal importance in model performance is defining the volume of the soil rooting zone, the basic water storage reservoir for the model. This requires knowledge of tree rooting depth and density, averaged for the trees to be modeled.

One avenue of future research could use the models to estimate some of these more difficult parameters. It may be easier to measure transpiration throughout a season, and with the model calculate back to the size of rooting zone that would have been required to sustain the observed activity. Similarly, interception and evaporation losses could be analyzed indirectly by measuring the duration and intensity of precipitation that is necessary before tree water stress recovery can be detected.

Another critical component of water stress modeling is dependable measures of biomass, particularly leaf area, and to a lesser extent, sapwood storage volume. Meteorological driving variables are critical to model performance. It became clear making simultaneous runs of H2OTRANS and DAYTRANS that many problems can develop when averaging meteorological data beyond acceptable limits. Whereas a single daily average soil temperature is fairly reasonable, a daily average incoming radiation value is less so, unless generated by an integrating data-logger. Even then the opportunity to model diurnal radiation thresholds and day length is lost.

With any modeling effort, decisions of temporal and spatial resolution must be balanced against the level of accuracy required. If high resolution predictions of diurnal ψ_l and k_l are required, H2OTRANS should be run on no larger site than a few hectares of even-aged trees, of a single species, on homogeneous topography. For more general seasonal estimates of transpiration and overall stress development, DAYTRANS could provide approximate answers over many hundreds of hectares occupied by a number of tree species.

Given the above considerations, these models have a variety of potential applications. They can provide a physiologically sensitive estimate of evapotranspiration (ET) for hydrologic and meteorologic studies. In studies researching processes sensitive to tree water stress, these models may provide a prediction of water stress.

For example, throughout the western United States forest stands periodically endure water stress sufficient to severely impede photosynthesis. Good correlations between model-predicted site water stress and site productivity (Grier and Running 1977, Running 1981) are likely. There may be a significant correlation between certain insect and disease epidemics and stress development in the host trees (Mattson and Addy 1975, Waring and Pitman 1980). A major component of fire danger rating systems is moisture content of the living fuels. Prediction of plant moisture content must entail a plant water stress model. Quantitative estimates of forest nutrient cycles require knowledge of soil and tree water movement.

These models should be tested on forest stands of varying species, age and structure under different physical and climatic conditions before any general use is attempted. A more extensive validation of H2OTRANS is in progress on eight different stands in southern Wyoming (Knight et al. 1984).

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APPENDIX 1.—Variable Notations.

$B\psi_l$	*predawn* leaf water potential, MPa, treated as positive values in these models
ψ_l	leaf water potential, MPa
k_l	leaf conductance to water vapor diffusion, cm s^{-1}
LA	tree or stand leaf area, cm^2
LAI	leaf area index, the ratio of canopy leaf area to ground area
ABSHD	absolute humidity deficit, g cm^{-3}
T	transpiration rate, cm^3 h^{-1}
TFD	transpiration flux density, g cm^{-2} s^{-1}
PT	potential transpiration, transpiration calculated with the maximum input k_l, cm^3 h^{-1}
R	total water flow resistance in the Soil-Plant-Atmosphere Continuum (SPAC), s cm^{-1}
DAYL	daylength, seconds
RH	relative humidity, %

APPENDIX 2.—Header File Format and Notes for H2OTRANS and DAYTRANS.
H2OTRANS Header File

Mnemonic	Card #	Columns	Format	Description	Default
MAXX	1	1-2	I2	NUMBER OF STATE VARIABLES	-
NEGX[1]		3	I1	OVERRIDE NEG. STATE VAR? 0 = NO, 1 = YES (DO NOT PRINT DIAGNOSTIC)	0
KSTART		4-6	I3	STARTING TIME	1
KSTOP[2]		7-10	I4	ENDING TIME	365
KSTEP		11-14	I4	TIME INCREMENT(DT)	1
MAXB[3]		16-17	I2	HIGHEST B CONSTANT INDEX	-
MAXG[4]		19-20	I2	TOTAL #G VALUES TO PRINT	-
MAXZ[4]		22-23	I2	TOTAL #Z VALUES TO PRINT	-
KPRINT		25-26	I2	PRINTER INTERVAL	KSTEP
KTHETA[5]		28-29	I2	PRINTER STARTING POINT-INCLUSIVE ITERATIONS FROM BEGINNING	0
NODUMP[6]	1	31-32	I2	"1" = DO NOT DUMP "0" = DUMP	0
JCT	2	14	A4	CARD(DUMP)DECK CODE	"SOWR"
T		5	9A8	TITLE	"STEVE RUNNING"
X(2,I)[7]	3	1-10	E10.4	INITIAL CONDITION STATE VAR #1 (8 PER CARD)	0.0
		11-20	E10.4	INITIAL CONDITION STATE VAR #2 (8 PER CARD)	0.0
B(I)[7,8]	(4)	1-10	E10.4	B(1) CONSTANT (8 PER CARD)	0.0
		11-20	E10.4	B(2) CONSTANT	0.0
IGP(I)[9]	(5)	1-2	I2	INDEX # OF G VALUE TO PRINT (20 MAXIMUM)	-
		3-4	I2		-
IZP(I)[9]	(6)	1-2	I2	INDEX 3 OF Z VALUE TO PRINT (10 MAXIMUM)	-
		3-4	I2		

HEADER FILE NOTES

1. NEGX—If this code is "0," a diagnostic is written for each state variable that becomes negative in value. To disable this diagnostic, type "1" on header record.

2. KSTOP—For hourly resolution model, compute: KSTOP = KSTART + (No. days · 24).

3. MAXB—Always enter the highest index number of B constants actually used.

4. MAXG. MAXZ—This is the total number of G values to print.

5. KTHETA—This feature works in conjunction with KPRINT1. Suppose KSTART = 200, KSTOP = 224, KPRINT = 12, and KTHETA = 0 (default). Printing will occur at 200, 211, and 223 (i.e. hours 1, 12, 24). If KTHETA = 3, printing occurs at 202 and 214 (i.e. hours 3, 15 and 24).

6. NODUMP—If "0," unit 62 must be available for writing upon; if "1," unit 62 is not used.

7. Card #3 begins initial conditions for state variables. With sequential numbering, 1 through 8, the first 8 state variables are initialized. On card #4, #9 through 16 are initialized, etc. Do not leave fields blank until the MAXX (or MAXB) number of variables has been reached. Do not skip any fields, as the processor has no way of determining the index number of the initial value except sequentially, starting with 1.

8. B constants are handled identically as X initial conditions. Values may be read in (punched) as floating point "F FORMAT." E FORMAT is not mandatory. However, some machines require E FORMAT numbers to be punched in a specific way. Check your FORTRAN reference manual at your installation for exact details.

9. These two cards contain the actual index numbers of the variables to print (G and Z variables). The only limitation is that they be less than or equal to the maximum number allowed (20 and 10 respectively for G and Z). The order of printing is as follows:

   X(1) THROUGH X(MAXX) - STATE VARIABLES,
   I(1) THROUGH I(MAXX) - FLOWS,
   G(i), $i \epsilon I^G$ = (IGP(j), j = 1, MAXG)
   Z(i), $i \epsilon I^Z$ = (IZP(J), J - 1, MAXZ)

   For the G's and Z's, the order of listing is the order of printing, (i.e. there is no resequencing system in the processor to reorder the G's and Z's in a sequential order if they are out of order.)

APPENDIX 3.—Input Format for H2OTRANS Driving Variables, Z(i).

Card	Columns	Format	Variable
1	1-4	A4	Site identification
	5-7	A3	Year
	8-10	F3.0	Julian date
	12-13	A2	Card ID
	14-17	F3.1	Daily precipitation
	18-20	F3.0	Soil temperature
2	1-4	A4	Site ID
	5-7	A3	Year
	8-10	A3	Julian date
	12-13	A3	Card ID
	15-17	F3.1	Incoming shortwave radiation (ly min^{-1})
	18-20	F3.0	Air temperature (°C)
	21-23	F3.0	Relative humidity (%)

Card 2 format is repeated on cards 2 through 5 to give 24 input sets per day on a total of five input cards per day.

APPENDIX 4.—Input Format for DAYTRANS Driving Variables, Z(i).

Card	Columns	Format	Variable
1	1-4	A4	Site ID
	6-7	A2	Year
	9-11	I3	Julian date
	14-16	F3.1	Air temperature (°C)
	18-20	F3.1	Night minimum air temperature (°C)
	22-23	F2.0	Relative humidity (%)
	25-28	F4.0	Average incoming SW radiation (ly min^{-1})
	30-32	F3.1	Soil temperature (°C)
	34-37	F4.2	Precipitation (cm)

One card is needed for each day.

```
      REAL*8 FNAM1,FNAM2,FNAM3
      INTEGER TTY
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
     2 NEGX,KTHETA,NODUMP
      DATA TTY,IN,IN1,IOUT/5,20,21,22/
      WRITE(TTY,5)
    5 FORMAT(' ENTER HEADER INPUT FILE NAME(MAX 10 CHAR): ',$)
      READ(TTY,6) FNAM1
    6 FORMAT(A10)
      WRITE(TTY,7)
    7 FORMAT(' ENTER DATA INPUT FILE NAME(MAX 10 CHAR): ',$)
      READ(TTY,6) FNAM2
      WRITE(TTY,8)
    8 FORMAT(' ENTER OUTPUT FILE NAME(MAX 10 CHAR): ',$)
      READ(TTY,6) FNAM3
      OPEN(UNIT=IN1,FILE=FNAM1)
      OPEN(UNIT=IN,FILE=FNAM2)
      OPEN(UNIT=IOUT,FILE=FNAM3)
      OPEN(UNIT=23,FILE='PSN.DAT')
C
C        MAIN PROGRAM, CALLS ALL SUBROUTINES
C        SHOULD NOT REQUIRE CHANGE
C
      CALL HEADER(IN1,TTY)
      K=KSTART
   10 CALL ZCOMP(IN)
      CALL PROCES
      CALL PHOTO
      WRITE(23,100) Z(1),G(67)
100   FORMAT(1X,F5.0,1X,F6.1)
      CALL FLOW
      CALL YCOMP
      CALL PRINT(IOUT)
      CALL UPDATE
      IF (K.GT.KSTOP-KSTEP) GO TO 20
      K=K+KSTEP
      GO TO 10
   20 K=KSTOP
      CALL ZERO
      CALL YCOMP
      CALL PRINT(IOUT)
      STOP
      END
      SUBROUTINE HEADER(IN1,TTY)
      INTEGER TTY
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
     2 NEGX,KTHETA,NODUMP
      DIMENSION IDUM(20)
C
C        READS HEADER INFORMATION CARDS
C        SHOULD NOT REQUIRE CHANGE
C
      READ(IN1,1000) MAXX,NEGX,KSTART,KSTOP,KSTEP,MAXB,MAXG,MAXZ,
     1  KPRINT,KTHETA,NODUMP,JCT,T
 1000 FORMAT(I2,I1,I3,2I4,6I3,/,21A4)
      IF (MAXX.LE.0.OR.MAXX.GT.20) CALL ERROR(5,MAXX,TTY)
      IF (MAXX.GT.16) GO TO 20
      IF (MAXX.GT.8) GO TO 10
```

```
      READ(IN1,1001) (X(2,I),I=1,8)
 1001 FORMAT (8E10.0)
      GO TO 30
   10 READ(IN1,1002) (X(2,I),I=1,16)
 1002 FORMAT (8E10.0,/,8E10.0)
      GO TO 30
   20 READ(IN1,1003) (X(2,I),I=1,20)
 1003 FORMAT (2(8E10.0,/),4E10.0)
   30 IF (MAXB.GT.32) GO TO 70
      IF (MAXB.GT.24) GO TO 60
      IF (MAXB.GT.16) GO TO 50
      IF (MAXB.GT.8) GO TO 40
      IF (MAXB.EQ.0) CALL ERROR(1,0,TTY)
      READ(IN1,2000) (B(I),I=1,8)
 2000 FORMAT (8E10.0)
      GO TO 170
   40 READ(IN1,2001) (B(I),I=1,16)
 2001 FORMAT (8E10.0,/,8E10.0)
      GO TO 170
   50 READ(IN1,2002) (B(I),I=1,24)
 2002 FORMAT (2(8E10.0,/),8E10.0)
      GO TO 170
   60 READ(IN1,2003) (B(I),I=1,32)
 2003 FORMAT (3(8E10.0,/),8E10.0)
      GO TO 170
   70 READ(IN1,2004) (B(I),I=1,40)
 2004 FORMAT (4(8E10.0,/),8E10.0)
  170 IF (MAXG.EQ.0) GO TO 180
      J=21-MAXG
      READ(IN1,3000) (IGP(I),I=1,MAXG),(IDUM(I),I=1,J)
 3000 FORMAT (21I2)
  180 J=11-MAXZ
      IF (MAXZ.EQ.0) GO TO 190
      READ(IN1,3001) (IZP(I),I=1,MAXZ),(IDUM(I),I=1,J)
 3001 FORMAT (11I2)
  190 IF (KSTART.EQ.0) KSTART=1
      IF (KSTOP.EQ.0) KSTOP=365
      IF (KSTEP.EQ.0) KSTEP=1
      IF (KPRINT.EQ.0) KPRINT=KSTEP
      IF (JCT.EQ.'    ') JCT='SOWR'
      DO 200 I=1,20
      IF (T(I).NE.'    ') GO TO 210
  200 CONTINUE
      T(1)='STEV'
      T(2)='E RU'
      T(3)='NNIN'
      T(4)='G   '
  210 RETURN
      END
      SUBROUTINE ZCOMP(IN)
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20)
C
C        READS CLIMATIC DATA CARDS
C        CHANGES IN CLIMATIC DATA INPUT FORMAT GO HERE
C     *  Z FUNCTIONS GO HERE
C     *  Z    DESCRIPTION
C        -    -----------
C        1    JULIAN DAY
C        2    PRECIPITATION (CM)
C        3    AIR TEMPERATURE (C)
```

```
C         4     RELATIVE HUMIDITY (PER CENT)
C         5     SOIL TEMPERATURE (C)
C         6     RADIATION (AVE. LANGLEYS PER MIN)
C         7     DAYLENGTH (SUNRISE-SUNSET)
C         8     NIGHT MINIMUM AIR TEMP. (C)
C
  100 FORMAT(8X,I3,F5.1,F4.1,F3.0,F5.2,F4.1,F5.2)
      READ(IN,100,END=50) JD,XTAIR,XTMIN,XRHUM,XRAD,XTSOIL,XPPT
      Z(1)=JD
      Z(2)=XPPT
      Z(3)=XTAIR
        ESD=6.1078*EXP((17.269*Z(3))/(237.3+Z(3)))
        ES=XRHUM/100.*ESD
        VPD=AMAX1((ESD-ES),0.0)
      Z(4)=217.E-6*VPD/(Z(3)+273.16)
      Z(5)=XTSOIL
      Z(6)=XRAD
        XD=JD-79.
        IF(XD .LT. 0.0)    XD=286.0+JD
        DAY=3.125*(SIN(XD*0.01721))+12.0
      Z(7)=DAY*3600*0.8
      Z(8)=XTMIN
      Z(12)=XRHUM
      Z(11)=VPD
   50 RETURN
      END
      SUBROUTINE UPDATE(TTY)
      INTEGER TTY
      COMMON K,X(2,20),F(20,20),DUM(380),MAXX,DUMM(47),NEGX
C
C         UPDATES STATE VARIABLES (COMPARTMENTS) AFTER EACH ITERATION
C         SHOULD NOT REQUIRE CHANGE
C
      DO 10 I=1,MAXX
      L=1
      X(2,I)=X(2,I)+X(1,I)
      IF (X(2,I).LT.0..AND.NEGX.EQ.0) CALL ERROR(2,L,TTY)
   10 CONTINUE
      RETURN
      END
      SUBROUTINE YCOMP
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ
C
C         PREPARES MATRIX OF COMPUTED VALUES FOR PRINTOUT
C         SHOULD NOT REQUIRE CHANGE
C
      DO 10 I=1,MAXX
      J=I+MAXX
      Y(I)=X(2,I)
   10 Y(J)=X(1,I)
      MAX2=2*MAXX
      DO 20 I=1,MAXG
      J=MAX2+I
      L=IGP(I)
   20 Y(J)=G(L)
      MAX3=MAX2+MAXG
      DO 30 I=1,MAXZ
      J=MAX3+I
      L=IZP(I)
```

```
   30 Y(J)=Z(L)
      RETURN
      END
      SUBROUTINE ERROR(I,J,TTY)
      INTEGER TTY
C
C        LIBRARY OF ERROR STATEMENTS CALLED WHEN MISTAKES ARE
C        MADE IN OTHER PART OF THE PROGRAM
C        SHOULD NOT REQUIRE CHANGE
C
      IF (I.LE.0 .OR. I.GE.8) GO TO 99
      GO TO (1,2,3,4,5,6,7),I
    1 WRITE(TTY,1001)
 1001 FORMAT(' ERROR IN B CONSTANTS.  MAXB=0',/)
      STOP
    2 WRITE(TTY,1002) J
 1002 FORMAT(' ERROR IN SUB. UPDATE - X(',I2,').LT.0.',/)
      RETURN
    3 WRITE(TTY,1003) J
 1003 FORMAT(' ERROR IN SUB. PROCESS.  G(',I2,') IS LT 0.',/)
      RETURN
    4 WRITE(TTY,1004) J
 1004 FORMAT(' ERROR IN SPECIAL FUNCTION (',I2,')',/)
      RETURN
    5 WRITE(TTY,1005) J
 1005 FORMAT(' ERROR IN NO. STATE VARIABLES.  MAXX=',I3,/)
      STOP
    6 WRITE(TTY,1006)
 1006 FORMAT(' ERROR IN YCOMP',/)
      RETURN
    7 WRITE(TTY,1007)
 1007 FORMAT(' ERROR IN SUB. ZCOMP.',/)
      RETURN
   99 WRITE(TTY,9000)  I
 9000 FORMAT (1H-,'ERROR IN SUB. ERROR.  ERROR CODE=',I3)
      END
      SUBROUTINE  FLOW
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20),DUM(160),MAXX
      DIMENSION X(20)
C
C        COUPLES FLOW BETWEEN COMPARTMENTS
C        NEW COMPARTMENTS OR NEW COUPLING BETWEEN COMPARTMENTS MUST GO HERE
C
      DO 10 I=1,20
      DO 10 J=1,20
      F(I,J)=0.0
   10 CONTINUE
      DO 20 I=1,MAXX
      X(I)=XS(2,I)
   20 CONTINUE
C
C     *  FLOW FUNCTIONS GO HERE
C
      F( 1, 2)=G(50)
      F( 2, 2)=G(1)
      F( 2, 3)=G(53)
      F( 2, 5)=G(51)
      F( 2, 6)=G(52)
      F( 3, 4)=G(29)
      F( 7, 7)=G(9)
```

```
      F( 8, 8)=G(62)
      F( 9, 9)=G(66)
      F(10,10)=G(67)
      DO 30 I=1,MAXX
      XS(1,I)=0.0
   30 CONTINUE
      DO 50 I=1,MAXX
      DO 50 J=1,MAXX
      PART=F(J,I)-F(I,J)
      IF (I.EQ.J) PART=F(I,I)
   50 XS(1,I)=XS(1,I)+PART
      RETURN
      END
      SUBROUTINE PROCES
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20),DUM(160),MAXX
      DIMENSION X(20)
C
C        AUXILIARY EQUATIONS USED IN THE STRUCTURE OF THE MODEL
C
      IF (IFLAG.NE.0) GO TO 20
      IFLAG=1
      DO 10 I=1,100
      G(I)=-1.0E32
   10 CONTINUE
   20 DO 30 I=1,MAXX
      X(I)=XS(2,I)
   30 CONTINUE
C
C     *  G FUNCTIONS GO HERE
C
      G(1)=AMAX1((Z(2)-(B(4)/B(7))*B(6))*B(7),0.0)
      G(2)=X(2)/B(2)
      G(3)=X(3)/B(3)
      G(4)=AMAX1(B(8)*Z(3)*B(7),0.0)
        IF(X(1) .LE. 0.0)  G(4)=0.0
      G(5)=B(4)/B(7)
      G(9)=Z(2)*B(7)-G(1)
      G(10)=AMAX1(B(10),0.2/G(2)+0.01*B(9),0.0)
      G(12)=10.*(1.0-EXP(-4.6*Z(6)))
      G(13)=1.-((G(5)-G(12))/G(5))
        IF(G(12) .GT. G(5)) G(13)=1.0
      G(14)=B(5)-(B(5)/(B(11)-B(10)))*(G(10)-B(10))
        IF(G(10) .GE. B(11)) G(14)=0.005
      G(15)=G(14)-(G(14)*0.05*(Z(4)*1.0E+6-4.0))
        IF(G(15) .LE. 0.0) G(15)=0.005
      G(16)=G(15)+G(15)*0.003*(Z(3)-10.0)
        IF(Z(8) .LT. 0.0) G(16)=AMAX1(G(15)+0.02*Z(8),0.005)
      G(17)=G(16)*G(13)
      G(18)=Z(4)*G(17)
      G(19)=G(18)*B(4)*Z(7)
      G(20)=G(17)/B(5)
      G(21)=G(19)/B(7)*10.
      G(50)=G(4)
        IF(X(1)-G(4) .LT. 0.0)  G(50)=X(1)
      G(51)=0.0
        IF((G(1)+G(4))/B(7) .GT. B(1))  G(51)=(G(50)-B(1))*B(7)
      G(52)=0.0
        IF(X(2)+G(50) .GT. B(2))  G(52)=X(2)+G(50)-G(51)-B(2)
      G(53)=B(3)-X(3)+G(19)
      G(55)=0.0
```

```
C
C  PENMON FUNCTION
C
      G(28)=PENMON(Z(3),Z(6),Z(11),G(5),G(17))
      G(29)=G(28)*B(4)*Z(7)
C
      RETURN
      END
      SUBROUTINE PHOTO
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160)
C
C       Z(10) = CANOPY AVERAGE RADIATION
C
      Z(10)=(Z(6)+Z(6)*EXP(-0.7*G(5)/2.))/2.
C
C       Z(9) = AVERAGE NIGHT TEMPERATURE
C
      Z(9)=(Z(3) + Z(8))/2.
C
      G(64)=((Z(10)-0.0143)/(Z(10)+0.322))*
     C(0.0182+0.0105*Z(3)-0.000194*(Z(3)**2))
      IF(G(64).LT.0.)G(64)=0.
      G(65)=(0.0006*(G(17)/1.6)*G(64))/
     C((G(17)/1.6)+G(64))
      G(62)=0.001*(24.-Z(7)/3600.)*EXP(0.2*Z(9))
      G(66)=G(65)*Z(7)
      G(67)=G(66)-G(62)
      RETURN
      END
      SUBROUTINE ZERO
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20)
C
C         ZEROS PARAMETERS IN MODEL
C         SHOULD NOT REQUIRE CHANGE
C
      DO 20 I=1,20
      X(1,I)=0.
      Z(I)=0.
      DO 20 J=1,20
   20 F(I,J)=0.0
      DO 30 I=1,100
   30 G(I)=0.0
      RETURN
      END
      SUBROUTINE PRINT(IOUT)
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
     2 NEGX,KTHETA,NODUMP
      DIMENSION XNULL(100),LBL(100,2),JK(10)
      DATA JK/1,8,15,22,29,36,43,50,57,64/
C
C         LABELS LINE PRINTER OUTPUT
C         ESTABLISHES OUTPUT FORMAT
C         PRINTS OUT ALL REQUESTED PARAMETERS
C         SHOULD NOT REQUIRE CHANGE
C
      IF (IFLAG.EQ.1) GO TO 30
      IFLAG=1
      DO 10 I=1,100
      XNULL(1)=0.0
```

```
      DO 10 J=1,2
   10 LBL(I,J)="  "
      J=100-MAXB
      WRITE (IOUT,1000) T,MAXX,(B(I),I=1,MAXB),
     1 (XNULL(I),I=1,J),KSTART,KSTOP,KSTEP
 1000 FORMAT("1",//,"1",//,5X,"KXBZ SIMULATION PROCESSOR",//,5X,20A4,//,
     1 5X,"STATE VARIABLES=",I2,//,5X,"B CONSTANTS=",//,
     2 10(5X,10(1X,1PG11.4),/),5X,"INITIAL TIME",3X,I3,//,5X,
     3 "TERMINATION",4X,I3,//,5X,"INCREMENT (DT)",1X,I3)
      MAX2=2*MAXX
      MAX3=MAX2+MAXG
      MY=MAX3+MAXZ
      JJ=100-MY
      IF (MY.LE.50) JJ=JJ-50
      DO 20 I=1,MY
      IF (I.LE.MAXX) LBL(I,1)="X("
      IF (I.GT.MAXX.AND.I.LE.MAX2) LBL(I,1)="I("
      IF (I.GT.MAX2.AND.I.LE.MAX3) LBL(I,1)="G("
      IF (I.GT.MAX3.AND.I.LE.MY) LBL(I,1)="Z("
   20 CONTINUE
      DO 21 I=1,MAXX
      ENCODE(3,2002,LBL(I,2)) I
 2002 FORMAT(I2,")")
   21 CONTINUE
      DO 22 I=1,MAXX
      J=MAXX+I
      ENCODE(3,2002,LBL(J,2)) I
   22 CONTINUE
      DO 23 I=1,MAXG
      J=MAX2+I
      L=IGP(I)
      ENCODE(3,2002,LBL(J,2)) L
   23 CONTINUE
      DO 24 I=1,MAXZ
      J=MAX3+I
      L=IZP(I)
      ENCODE(3,2002,LBL(J,2)) L
   24 CONTINUE
   30 IF (KFLAG.EQ.1) GO TO 40
      KFLAG=1
      ICT=0
      WRITE(IOUT,2000) T
 2000 FORMAT("1",//,5X,20A4,/)
      WRITE(IOUT,2001) ((LBL(I,J),J=1,2),I=1,100)
 2001 FORMAT("    TIME",10(7X,A2,A3),/,9(8X,10(7X,A2,A3),/))
      ICT=ICT+15
   40 IF (MOD(K-KSTART+1+KPRINT-KTHETA,KPRINT).NE.0) GO TO 60
      IF (MY.LE.50) GO TO 50
      WRITE (IOUT,3000) K,(Y(I),I=1,MY),(XNULL(I),I=1,JJ)
 3000 FORMAT(3X,I4,10(1X,1PG11.4),/,9(7X,10(1X,1PG11.4),/))
      ICT=ICT+11
      GO TO 60
   50 WRITE (IOUT,3001) K,(Y(I),I=1,MY),(XNULL(I),I=1,JJ)
 3001 FORMAT(3X,I4,10(1X,1PG11.4),/,4(7X,10(1X,1PG11.4),/))
      ICT=ICT+6
   60 IF (ICT.GT.50) KFLAG=0
      IF (NODUMP.EQ.1) RETURN
      OPEN(UNIT=23,FILE="DUMP.DAT")
      KK=0
      DO 70 I=1,MY,7
```

```
      J1=I
      J2=I+6
      KK=KK+1
      WRITE(23,4000) JCT,K,JK(KK),(Y(L),L=J1,J2)
 4000 FORMAT (A4,I4,1X,I2,7E10.3)
   70 CONTINUE
      RETURN
      END
      FUNCTION PENMON(TAIR,RAD,VPD,XLAI,COND)
      GAMMA=0.646+0.0006*TAIR
      PLAI=XLAI/2.
      T1=TAIR+0.5
      T2=TAIR-0.5
      SVP1=6.1078*EXP((17.269*T1)/(237.0+T1))
      SVP2=6.1078*EXP((17.269*T2)/(237.0+T2))
      SLOPE=SVP1-SVP2
      XNETR=RAD*0.8*697.3
      CP=1.01E+3
      PA=1.292-0.00428*TAIR
      RA=5.0
      RS=100./COND
      XLAT=(2.501 - 0.0024*TAIR) * 1.0E+6
      XTRANS=((SLOPE*XNETR)/PLAI+(CP*PA)*(VPD/RA))/
     C(SLOPE+GAMMA*(1.0+RS/RA))
      PENMON=XTRANS/(XLAT * 10.)
      RETURN
      END
      FUNCTION S4(K)
C
C        SETS MODEL STARTING POINT TO REQUESTED JULIAN DATE
C        REGARDLESS OF DATA.
C        SHOULD NOT REQUIRE CHANGE
C
      IN=20
   10 READ(IN,1000,END=20) KD
 1000 FORMAT( 7X,I3)
      IF (K.GT.KD) GO TO 10
      BACKSPACE IN
      S4=1.
      RETURN
   20 REWIND IN
      IFLAG=IFLAG+1
      IF (IFLAG.EQ.2) STOP
      GO TO 10
      END
```

```
C      DATA FILE INPUT STATEMENTS
C
       REAL*8 FNAM1,FNAM2,FNAM3
       INTEGER TTY
       COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
      1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
      2 NEGX,KTHETA,NODUMP
       DATA TTY,IN,IN1,IOUT/5,20,21,22/
       WRITE(TTY,5)
     5 FORMAT(' ENTER HEADER INPUT FILE NAME(MAX 10 CHAR): ',$)
       READ(TTY,6) FNAM1
     6 FORMAT(A10)
       WRITE(TTY,7)
     7 FORMAT(' ENTER DATA INPUT FILE NAME(MAX 10 CHAR): ',$)
       READ(TTY,6) FNAM2
       WRITE(TTY,8)
     8 FORMAT(' ENTER OUTPUT FILE NAME(MAX 10 CHAR): ',$)
       READ(TTY,6) FNAM3
       OPEN(UNIT=IN1,FILE=FNAM1)
       OPEN(UNIT=IN,FILE=FNAM2)
       OPEN(UNIT=IOUT,FILE=FNAM3)
C
C      MAIN PROGRAM, CALLS SUBROUTINES
C
       CALL HEADER(IN1,TTY)
       K=KSTART
    10 CALL ZCOMP
       CALL PROCES
       CALL FLOW
       CALL YCOMP
       IF(Z(6).EQ. 0.0) GO TO 15
       CALL PRINT(IOUT)
    15 CONTINUE
       CALL UPDATE(TTY)
       IF (K.GT.KSTOP-KSTEP) GO TO 20
       K=K+KSTEP
       GO TO 10
    20 K=KSTOP
       CALL ZERO
       CALL YCOMP
       CALL PRINT(IOUT)
       STOP
       END
C
       SUBROUTINE HEADER(IN1,TTY)
       COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
      1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
      2 NEGX,KTHETA,NODUMP
       DIMENSION IDUM(20)
       READ(IN1,1000) MAXX,NEGX,KSTART,KSTOP,KSTEP,MAXB,MAXG,MAXZ,
      1  KPRINT,KTHETA,NODUMP,JCT,T
 1000 FORMAT(I2,I1,I3,2I4,6I3,/,21A4)
       IF (MAXX.LE.0 .OR. MAXX.GT.20) CALL ERROR (5,MAXX,TTY)
       IF (MAXX.GT.16) GO TO 20
       IF (MAXX.GT.8) GO TO 10
       READ(IN1,1001) (X(2,I),I=1,8)
 1001 FORMAT (8E10.0)
       GO TO 30
   10  READ(IN1,1002) (X(2,I),I=1,16)
 1002 FORMAT (8E10.0,/,8E10.0)
```

```
      GO TO 30
   20 READ(IN1,1003) (X(2,I),I=1,20)
 1003 FORMAT (2(8E10.0,/),4E10.0)
   30 IF (MAXB.GT.32) GO TO 70
      IF (MAXB.GT.24) GO TO 60
      IF (MAXB.GT.16) GO TO 50
      IF (MAXB.GT.8) GO TO 40
      IF (MAXB.EQ.0) CALL ERROR(1,0,TTY)
      READ(IN1,2000) (B(I),I=1,8)
 2000 FORMAT (8E10.0)
      GO TO 170
   40 READ(IN1,2001) (B(I),I=1,16)
 2001 FORMAT (8E10.0,/,8E10.0)
      GO TO 170
   50 READ(IN1,2002) (B(I),I=1,24)
 2002 FORMAT (2(8E10.0,/),8E10.0)
      GO TO 170
   60 READ(IN1,2003) (B(I),I=1,32)
 2003 FORMAT (3(8E10.0,/),8E10.0)
      GO TO 170
   70 READ(IN1,2004) (B(I),I=1,40)
 2004 FORMAT (4(8E10.0,/),8E10.0)
  170 IF (MAXG.EQ.0) GO TO 180
      J=21-MAXG
      READ(IN1,3000) (IGP(I),I=1,MAXG),(IDUM(I),I=1,J)
 3000 FORMAT (21I2)
  180 J=11-MAXZ
      IF (MAXZ.EQ.0) GO TO 190
      READ(IN1,3001) (IZP(I),I=1,MAXZ),(IDUM(I),I=1,J)
 3001 FORMAT (11I2)
  190 IF (KSTART.EQ.0) KSTART=1
      IF (KSTOP.EQ.0) KSTOP=365
      IF (KSTEP.EQ.0) KSTEP=1
      IF (KPRINT.EQ.0) KPRINT=KSTEP
      IF (JCT.EQ.4H    ) JCT=4HSOWR
      DO 200 I=1,9
      IF (T(I).EQ.8H        ) GO TO 200
      GO TO 210
   200 CONTINUE
      T(1)='STEV'
      T(2)='E RU'
      T(3)='NNIN'
      T(4)='G   '
   210 CONTINUE
      RETURN
      END
C
      SUBROUTINE ZCOMP
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20)
C
C     *  Z    DESCRIPTION
C        -    -----------
C        1    JULIAN DAY
C        2    PRECIPITATION (CM)
C        3    AIR TEMPERATURE (C)
C        4    RELATIVE HUMIDITY (%)
C        5    SOIL TEMP (C)
C        6    RADIATION (LANGLEYS PER MIN)
C        7    HOUR OF DAY
      DIMENSION VAL(10,24)
```

```
      IF (IFLAG.NE.0) GO TO 10
      IFLAG=1
      XI=S4(K)
      IF (XI.NE.1.) STOP
   10 CONTINUE
C
C     *  Z FUNCTIONS GO HERE
C
      XI = S2( VAL (1,1) )
      Z(1) = VAL(1,1)
      Z(2) = VAL(2,1)
      Z(3) = VAL(5,1)
      Z(4) = VAL(6,1)
      Z(5) = VAL(3,1)
      Z(6) = VAL(4,1)
      Z(7) = Z(7) + 1.0
      IF (Z(7) .GE. 25.0)  Z(7) = 1.0
      RETURN
      END
C
      SUBROUTINE UPDATE(TTY)
      INTEGER TTY
      COMMON K,X(2,20),F(20,20),DUM(380),MAXX,DUMM(47),NEGX
      DO 10 I=1,MAXX
      L=I
      X(2,I)=X(2,I)+X(1,I)
      IF (X(2,I).LT.0. .AND. NEGX.EQ.0) CALL ERROR(2,L,TTY)
   10 CONTINUE
      RETURN
      END
C
      SUBROUTINE YCOMP
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ
      DO 10 I=1,MAXX
      J=I+MAXX
      Y(I)=X(2,I)
      Y(J)=X(1,I)
   10 CONTINUE
      DO 20 I=1,MAXG
      J=2*MAXX+I
      L=IGP(I)
      Y(J)=G(L)
   20 CONTINUE
      DO 30 I=1,MAXZ
      J=2*MAXX+MAXG+I
      L=IZP(I)
      Y(J)=Z(L)
   30 CONTINUE
      RETURN
      END
C
      SUBROUTINE ERROR (I,J,TTY)
      INTEGER TTY
      IF (I.LE.0 .OR. I.GE.8) GO TO 99
      GO TO (1,2,3,4,5,6,7),I
    1 WRITE(TTY,1001)
 1001 FORMAT(1H0,'ERROR IN B CONSTANTS.  MAXB=0',/)
      STOP
    2 WRITE(TTY,1002) J
```

```
 1002 FORMAT (1H0,'ERROR IN SUB. UPDATE - X(',I2,').LT.0.',/)
      RETURN
    3 WRITE(TTY,1003) J
 1003 FORMAT (1H0,'ERROR IN SUB. PROCES.  G(',I2,') IS LT 0.',/)
      RETURN
    4 WRITE(TTY,1004) J
 1004 FORMAT (1H0,'ERROR IN SPECIAL FUNCTION (',I2,')',/)
      RETURN
    5 WRITE(TTY,1005) J
 1005 FORMAT (1H0,'ERROR IN NO. STATE VARIABLES.  MAXX=',I3,/)
      STOP
    6 WRITE(TTY,1006)
 1006 FORMAT (1H0,'ERROR IN YCOMP',/)
      RETURN
    7 WRITE(TTY,1007)
 1007 FORMAT (1H0,'ERROR IN SUB. ZCOMP.',/)
      RETURN
   99 WRITE(TTY,9000)  I
 9000 FORMAT (1H-,'ERROR IN SUB. ERROR.  ERROR CODE=',I3)
      END
C
      SUBROUTINE  FLOW
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20),DUM(160),MAXX
      DIMENSION X(20)
      DO 10 I=1,20
      DO 10 J=1,20
      F(I,J)=0.0
   10 CONTINUE
      DO 20 I=1,MAXX
      X(I)=XS(2,I)
   20 CONTINUE
C
C     *  FLOW FUNCTIONS GO HERE
C
      F(3,3)=G(50)-G(53)
      F(1,3)=G(51)
      F(3,2)=G(54)
      F(3,4)=G(55)
      F(4,5)=G(56)
      F(5,6)=G(57)
      F(8,9)=G(18)
      F(7,8)=G(62)
      F(4,7)=G(67)
      F(5,7)=G(68)
      F(10,10)=G(53) + G(58)
      DO 30 I=1,MAXX
      XS(1,I)=0.0
   30 CONTINUE
      DO 50 I=1,MAXX
      DO 40 J=1,MAXX
      IF (I.EQ.J) GO TO 60
      XS(1,I)=XS(1,I)+F(J,I)-F(I,J)
   40 CONTINUE
   50 CONTINUE
      RETURN
   60 XS(1,I)=XS(1,I)+F(I,I)
      GO TO 40
      END
C
      SUBROUTINE PROCES
```

```
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20),DUM(160),MAXX
      DIMENSION X(20)
      IF (IFLAG.NE.0) GO TO 20
      IFLAG=1
      DO 10 I=1,100
      G(I)=-1.0E32
   10 CONTINUE
   20 DO 30 I=1,MAXX
      X(I)=XS(2,I)
   30 CONTINUE
C
C     *  G FUNCTIONS GO HERE
C
      G(1)=S3(Z(3),Z(4))
      G(2)=B(9)/B(10)
      G(3)=X(3)/B(3)
      G(4)=X(4)/B(4)
      G(5)=X(5)/B(5)
      G(6)=(G(4)+G(5))/2.
      G(7)=X(7)/B(7)
      G(10)=AMAX1(B(13),0.2/G(6)+0.01*B(11),0.0)
      G(11)=10.*(1.0-EXP(-4.6*Z(6)))
      G(12)=1.0-(G(2)-G(11))/G(2)
      IF(G(11).GT.G(2)) G(12)=1.0
      G(13)=AMAX1(B(12)-(B(12)/(B(14)-B(13)))*(G(10)-B(13)),0.005)
      IF(G(10).LT.B(13)) G(13)=B(12)
      G(14)=G(13)-(G(13)*.05*(G(1)*1.0E6-4.))
      IF(G(14) .LE. 0.0) G(14)=0.005
      G(15)=S1(Z(3),Z(7),G(14))
      G(16)=G(15)*G(12)
      G(17)=G(16)*G(1)
      G(18)=G(17)*B(9)*3600.
C
      IF(Z(7) .GT. 4.)Z(2)=0.0
      G(50)=AMAX1((Z(2)/4.-B(6)*(B(9)/B(10)))*B(10),0.0)
      G(51)=AMIN1(Z(3)*B(1)*B(10),X(1))
      IF(Z(3).LE.0.0) G(51)=0.0
      G(52)=EXP(5.*(G(3)-1.0))
      G(53)=G(52)*G(1)*B(10)*3600.
      IF(G(3).LE.0.0) G(53)=0.
      IF(X(1).GT.0.) G(53)=0.
      G(54)=AMAX1((G(50)+G(51)-(B(2)*B(10))),0.)
      G(55)=AMAX1((G(50)+G(51)-G(53)-G(54))-(B(3)-X(3)),0.0)
      G(56)=AMAX1(G(55)-(B(4)-X(4)),0.0)
      G(57)=AMAX1(G(56)-(B(5)-X(5)),0.0)
      G(58)=(Z(2)/4.)*B(10)-G(50)
C
      G(60)=B(8)*(1.-G(10)/B(14)+B(13)/B(14))
      G(61)=X(8)/B(16)
      G(62)=0.
      IF(G(61).GE.G(18)) G(62)=AMAX1(G(60)-X(8),G(18)/B(16))
      IF(G(61).LT.G(18)) G(62)=G(18)-G(61)
      G(66)=X(7)/B(17)
      G(67)=AMIN1(G(62)-G(66),(B(7)-X(7))/B(17),X(4)/B(17))
      G(68)=AMIN1(G(62)-G(66)-G(67),(B(7)-X(7))/B(17))
      G(69)=G(67)+G(68)
C
      IF(Z(5) .LT. 0.0)G(70)=10.0
      IF(Z(5) .GT. 0.0) G(70)=1.0/Z(5)
      G(71)=-0.28+2.*G(10)
```

```
      G(72)=G(70)+G(71)
      G(73)=AMIN1(G(10)+G(72)*(G(69)*278./B(9)),B(14))
      G(76)=G(16)/B(12)
      G(77)=G(18)/B(10)*10.
      G(78)=0.0
      RETURN
      END
C
      SUBROUTINE ZERO
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20)
      DO 10 I=1,20
      X(1,I)=0.0
      Z(I)=0.0
   10 CONTINUE
      DO 20 I=1,20
      DO 20 J=1,20
      F(I,J)=0.0
   20 CONTINUE
      DO 30 I=1,100
      G(I)=0.0
   30 CONTINUE
      RETURN
      END
C
      SUBROUTINE PRINT(IOUT)
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
     2 NEGX,KTHETA,NODUMP
      DIMENSION XNULL(100),LBL(100,2),JK(10)
      DATA JK/1,8,15,22,29,36,43,50,57,64/
      IF (IFLAG.EQ.1) GO TO 30
      IFLAG=1
      DO 10 I=1,100
      XNULL(I)=0.0
      DO 10 J=1,2
   10 LBL(I,J)=' '
      J=100-MAXB
      WRITE(IOUT,1000) T,MAXX,(B(I),I=1,MAXB),
     1 (XNULL(I),I=1,J),KSTART,KSTOP,KSTEP
 1000 FORMAT ('1',/,'1',/,5X,'KXBZ SIMULATION PROCESSOR',/,5X,20A4,/,
     1 5X,'STATE VARIABLES=',I2,/,5X,'B CONSTANTS=',/,
     2 10(5X,10(1X,1PG11.4),/),5X,'INITIAL TIME',3X,I4,/,5X,
     3 'TERMINATION',4X,I4,/,5X,'INCREMENT (DT)',1X,I4)
      MAX2=2*MAXX
      MAX3=MAX2+MAXG
      MY=MAX3+MAXZ
      JJ=100-MY
      IF (MY.LE.50) JJ=JJ-50
      DO 20 I=1,MY
      IF (I.LE.MAXX) LBL(I,1)='X('
      IF (I.GT.MAXX.AND.I.LE.MAX2) LBL(I,1)='I('
      IF (I.GT.MAX2.AND.I.LE.MAX3) LBL(I,1)='G('
      IF (I.GT.MAX3.AND.I.LE.MY) LBL(I,1)='Z('
   20 CONTINUE
      DO 21 I=1,MAXX
      ENCODE (3,2002,LBL(I,2)) I
 2002 FORMAT(I2,')')
   21 CONTINUE
      DO 22 I=1,MAXX
      J=MAXX+I
```

```
      ENCODE (3,2002,LBL(J,2)) I
   22 CONTINUE
      DO 23 I=1,MAXG
      J=MAX2+I
      L=IGP(I)
      ENCODE (3,2002,LBL(J,2)) L
   23 CONTINUE
      DO 24 I=1,MAXZ
      J=MAX3+I
      L=IZP(I)
      ENCODE (3,2002,LBL(J,2)) L
   24 CONTINUE
   30 IF (KFLAG.EQ.1) GO TO 40
      KFLAG=1
      ICT=0
      WRITE(IOUT,2000) T
 2000 FORMAT('1',5X,20A4,/)
      WRITE(IOUT,2001) ((LBL(I,J),J=1,2),I=1,100)
 2001 FORMAT (4X,'TIME',10(3X,A2,A3,4X),/,9(8X,10(3X,A2,A3,4X),/))
      ICT=ICT+13
   40 IF (MOD(K-KSTART+1+KPRINT-KTHETA,KPRINT).NE.0) GO TO 60
      IF (MY.LE.50) GO TO 50
      WRITE(IOUT,3000) K,(Y(I),I=1,MY),(XNULL(I),I=1,JJ)
 3000 FORMAT (3X,I4,10(1X,1PG11.4),/,9(7X,10(1X,1PG11.4),/))
      ICT=ICT+11
      GO TO 60
   50 WRITE(IOUT,3001) K,(Y(I),I=1,MY),(XNULL(I),I=1,JJ)
 3001 FORMAT(3X,I4,10(1X,1PG11.4),/,4(7X,10(1X,1PG11.4),/))
      ICT=ICT+6
   60 IF (ICT.GT.50) KFLAG=0
      IF (NODUMP.EQ.1) RETURN
      OPEN(UNIT=23,FILE='DUMP.DAT')
      KK=0
      DO 70 I=1,MY,7
      J1=I
      J2=I+6
      KK=KK+1
      WRITE (23,4000) JCT,K,JK(KK),(Y(L),L=J1,J2)
 4000 FORMAT (A4,I4,1X,I2,7E10.3)
   70 CONTINUE
      RETURN
      END
C
      FUNCTION S1(TAIR,XHOUR,COND)
      IF(XHOUR-5.) 91,90,91
 90   SRT=TAIR
 91   IF(SRT.GT.0) GO TO 92
      S1=AMAX1(COND+0.02*SRT,0.005)
      IF(SRT.LT.-7.) S1=0.005
      GO TO 93
 92   S1=COND+COND*0.003*(TAIR-10.0)
 93   RETURN
      END
C
      FUNCTION S2 (VAL)
      DIMENSION VAL(10,24)
      IN=20
      IF (IFLAG.EQ.1) GO TO 20
      READ (IN,1000) (VAL(I,1),I=1,3),((VAL(I,J),I=4,6),J=1,6),
     1 ((VAL(I,J),I=4,6),J=7,12),((VAL(I,J),I=4,6),J=13,18),
```

```
     2 ((VAL(I,J),I=4,6),J=19,24)
 1000 FORMAT (7X,F3.0,4X,F3.1,F3.0,/,3(14X,6(F3.1,2F3.0),/),
     1 14X,6(F3.1,2F3.0))
     6 K=1
       IFLAG=1
       DO 10 I=2,24
       VAL(1,I)=VAL(1,1)
       VAL(2,I)=VAL(2,1)
       VAL(3,I)=VAL(3,1)
    10 CONTINUE
       S2=1.
       K = K + 1
       RETURN
    20 DO 40 J=1,10
       DO 30 I=2,24
       VAL(J,I-1)=VAL(J,I)
    30 CONTINUE
       VAL(J,24)=0.0
    40 CONTINUE
       IF (K.EQ.24) IFLAG=0
       K=K+1
       S2=2.
       RETURN
       END
C
       FUNCTION S3(TA,RH)
C      ******ABSOLUTE HUMIDITY DEFICIT (AIR TEMP, REL HUM)
       ESD = 6.1078 * EXP ((17.269 * TA)/ (237.3 + TA))
       ES=RH/100.*ESD
C      ******    IN THE EVENT DEW IS GTR THAN AIR, RETURN ZERO
       VPD = AMAX1((ESD - ES), 0.0)
       S3= 217.E-6 * VPD / (TA + 273.16)
       RETURN
       END
C
       FUNCTION S4(K)
       IN=20
    10 READ (IN,1000,END=20) KD
 1000 FORMAT( 7X,I3)
    15 IF (K.GT.KD) GO TO 10
       BACKSPACE IN
       S4=1.
       RETURN
    20 REWIND IN
       IFLAG=IFLAG+1
       IF (IFLAG.EQ.2) STOP
       GO TO 10
       END
```


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Running, Steven W. 1984. Documentation and preliminary validation of H2OTRANS and DAYTRANS, two models for predicting transpiration and water stress in western coniferous forests. USDA Forest Service Research Paper RM-252, 45 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Two stand-level hydrologic computer models have been developed to study water flow through western coniferous forest ecosystems. The models, H2OTRANS and DAYTRANS, are for hourly and daily timesteps, respectively, and use routine meteorological data. Required parameters include leaf area index, sapwood basal area, and soil storage capacity. The models incorporate rates of snowmelt, precipitation, canopy interception, and litter and soil evaporation. Primary model outputs are transpiration, soil moisture depletion, subsurface outflow, and tree water stress development as measured by leaf water potential and leaf conductance. Complete documentation of all equations is presented, as are the results from an initial validation on lodgepole pine at the Fraser Experimental Forest in Colorado. A sensitivity analysis of the models and a discussion of their range of applicability is also presented.

Keywords: Ecosystem model, hydrology model, tree water stress, computer simulation, transpiration model, water potential, leaf conductance

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

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Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

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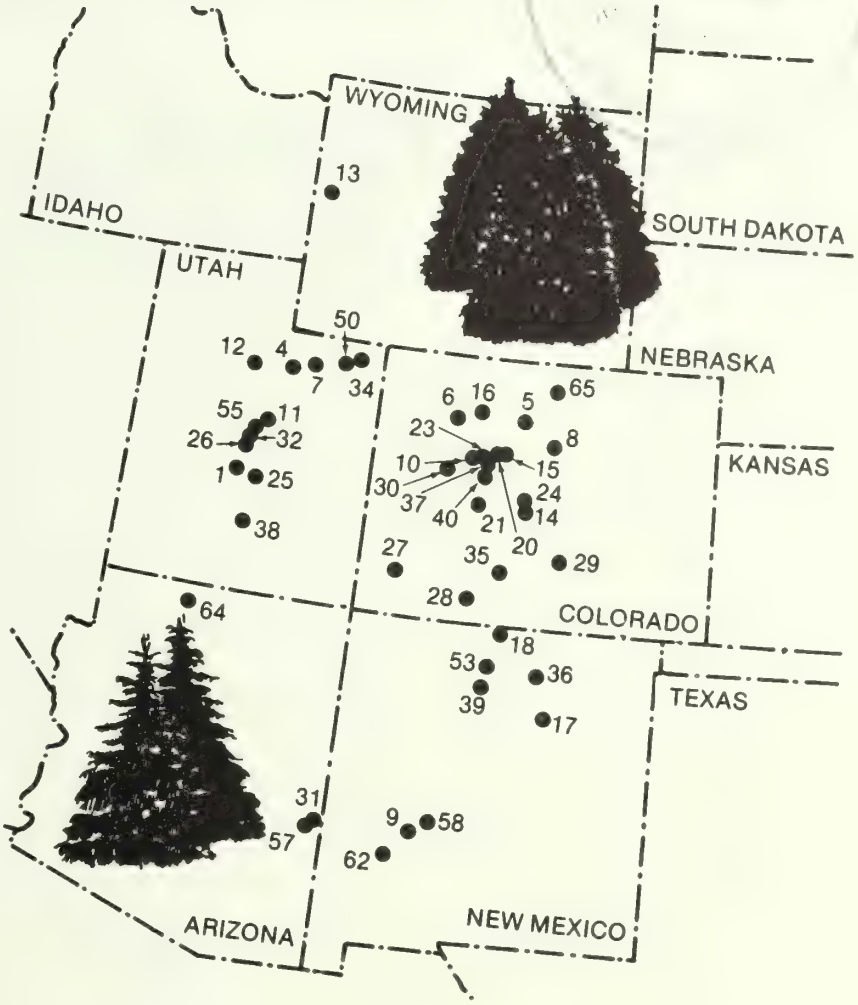
*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526

Genetic Variation in Blue Spruce: A Test of Populations in Nebraska

David F. Van Haverbeke



Research Paper RM-253
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

Abstract

Analyses of 43 blue spruce populations, at age 12 (9 years in the field) revealed significant differences among populations for survival, height, vigor, crown diameter, frost injury, and foliage color. Use of regions increases the probability of locating better seed sources, but high variability among individual populations within regions limits their value in specifying where better seed sources can be collected. Phenotypes should be selected in best stands within regions.

SDA Forest Service
search Paper RM-253

May 1984

Genetic Variation in Blue Spruce: A Test of Populations in Nebraska

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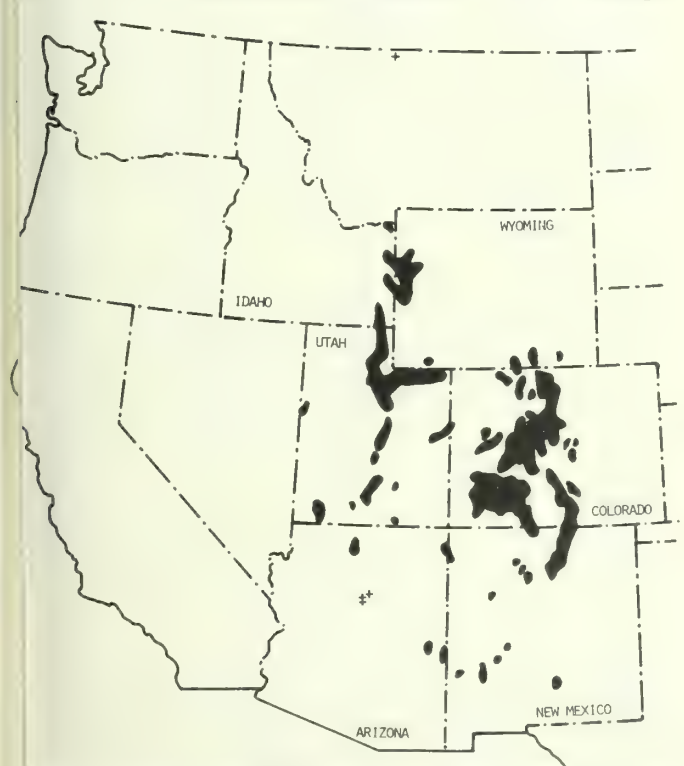
Management Implications

The Great Plains is a region with few native evergreen species. One of the objectives of tree improvement research in this region is to introduce, test, and identify adapted seed sources of coniferous species for use in Great Plains windbreak, environmental improvement and esthetic plantings.

Blue spruce (*Picea pungens* Engelm.), because of its desirable foliage color and symmetry, is a highly valued species in the northern half of the United States and in Canada for landscaping and Christmas tree production. Because it is cold-hardy, drought-resistant, and long-lived, blue spruce is also a desirable species for use in shelterbelt plantings, especially in the eastern part of the central and northern Great Plains and in the Prairie Provinces of Canada. Identification of blue spruce seed sources that are adapted to particular planting sites would increase the number of evergreen species suitable for planting in the North American prairie-plains.

Introduction

Blue spruce is native to the central Rocky Mountain region of the United States (fig. 1). Stands of this species extend from northcentral Montana, south through southern and western Wyoming and eastern Idaho, Utah, northern central and eastern Arizona, southern, western and northern New Mexico, and central Colorado (Little 1971 and 1979, Jones and Rietveld 1974, Hanover 1975, Strong 1978). Blue spruce usually grows at montane elevations of 1,800 to 2,600 m, occasionally reaching into the subalpine zone up to 3,100 m in the southernmost part of its range (Fechner 1980). Trees grow singly, or in small groups, along the banks of streams and in broad, cool, humid and grassy valleys. Blue spruce is a relatively slow growing conifer that eventually attains great size and is long-lived. Its native habitats are characterized by cool summers and dry winters, although snowfall is usually high at most sites. The species is drought-resistant and cold-tolerant.



gure 1.—Natural range of blue spruce (after Little 1971 and Hanover 1975).

Blue spruce may grow in association with the closely related Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.); however, Engelmann spruce is typically a subalpine (2,750 to 3,350 m elevation) species. Although the two species are usually isolated from each other, sometimes they are associated in scattered zones of altitudinal overlap throughout much of the blue spruce range (Fowler and Roche 1975). Hybridization either does not occur (Daubenmire 1972), or occurs infrequently because of various pre-fertilization incompatibilities (Fechner and Clark 1969, Kossuth and Fechner 1973).

The plantation reported on here is part of a regional test of blue spruce populations for which 2-year nursery performances (Hanover and Reicosky 1972), and five-year field performances in Canada (Canada Dep. Reg. Econ. Exp. 1979) and in northern United States and Canada (Bongarten 1978) were reported. Nine-year field (12 years from sowing) performances of the populations in the Nebraska plantations are reported here.

Material and Methods

Seedling stock for this test originated from seed collected in the fall of 1969 from more than 400 trees throughout the natural range of blue spruce (Hanover and Reicosky 1972). The seed was sown in single-tree lots, in an East Lansing, Mich. nursery, in 1970. In 1972, the 2+0 stock was shipped to 17 cooperators throughout the northcentral region of the United States and Canada. The seedlings were field-planted in the spring of 1973 as 2+1 stock, following transplanting by individual cooperators. Prior to shipment, progenies of individual trees sampled from the same locale were combined to form populations. Material for the Nebraska test contained 43 populations consisting of seedlings from 1 to 22 parent trees per population (fig. 2, table 1).

The plantation is located approximately 90 km east of Lincoln, in southeast Nebraska (41°00′ N latitude, 96°52′ W longitude), on a silty clay loam soil derived

from loess with a gently sloping, southeast-facing slope. The growing season averages 170 days, and the mean annual precipitation is 760 mm, of which approximately 75% falls during the growing season. The elevation is 305 m.

Seedlings were machine-planted in a randomized complete block design of 4-tree linear plots with 5 replications. Seedlings were spaced 2.4 m apart within rows 4.5 m apart.

Survival (%), height and crown diameter (m), vigor (mean annual height increment for the last 4 years), frost injury (scale of 0 to 3, with 0 = light, 3= heavy), and winter foliage color (scale of 0 to 8) were recorded in fall 1981 and evaluated. Foliage color was qualified utilizing Ridgway's (1912) color standards and nomenclature (Appendix).

Data were analyzed on the basis of: (1) all 43 populations as individuals and (2) a partitioning of the 43 populations into six regional groups based on latitude and longitude. The latter analysis was intended to detect possible regions of superior performance, wherein, each group was considered as a "population" and the populations within each group as a sample of those available. This yielded an analysis of regional differences based on an error variance formed from the variation among populations in each regional group.

Results

Survival

Survival percentages among the 43 blue spruce populations after 9 field seasons (12 years from sowing) averaged 68.4%, ranging from 25% to 90% (table Chi-square analysis revealed significant differences percent survival among the populations (X^2 = 94.5) (P 0.05) (table 2A). The 43 populations could be partition into three segments, with populations in the highest a

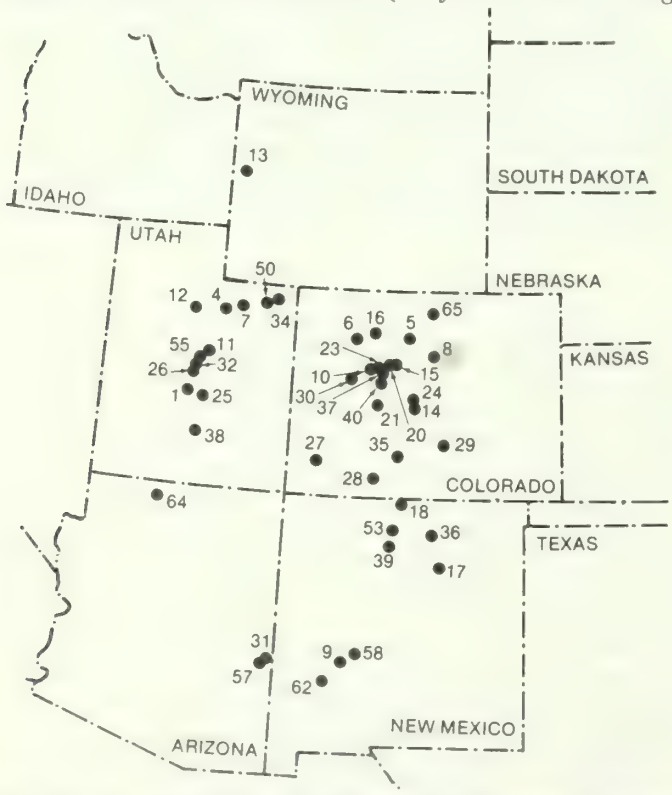


Figure 2.—Locations of blue spruce populations tested in eastern Nebraska (after Hanover 1975).

Table 1.—Identities and survival of blue spruce populations ir eastern Nebraska

Regional groups	Pop. no.	Parent trees in pop.	Survi
		no.	*perce*
I	4	6	85.(
Wyoming	7	4	75.(
No. Utah	12	8	90.(
	13	18	80.(
	34	1	25.(
	50	8	80.(
Sub-total & $\bar{X}$		45	72.5
II	5	6	60.(
No. Colorado	6	7	75.(
	8	11	80.(
	16	7	80.(
	65	20	70.(
Sub-total & $\bar{X}$		51	73.(
III	1	4	70.(
Central Utah	11	10	85.(
	25	4	55.(
	26	2	80.(
	32	5	75.(
	38	8	85.(
	55	1	90.(
Sub-total & $\bar{X}$		34	77.1
IV	10	13	65.(
Central	14	10	70.(
Colorado	15	9	70.(
	20	1	70.(
	21	3	85.(
	23	1	50.(
	24	10	80.(
	30	2	50.(
	37	8	60.(
	40	12	60.(
Sub-total & $\bar{X}$		69	66.(
V	17	5	61.1
So. Colorado	18	1	35.(
No. Arizona	27	9	85.(
No. New Mexico	28	7	65.(
	29	9	30.(
	35	13	90.(
	36	9	45.(
	39	11	60.(
	53	10	65.(
	64	7	65.(
Sub-total & $\bar{X}$		81	60.1
VI	9	3	65.(
So. Arizona	31	22	80.(
So. New Mexico	57	2	65.(
	58	6	60.(
	62	4	70.(
Sub-total & $\bar{X}$		37	68.(
Grand total & $\bar{X}$		317	68.4

Table 2.—Analysis of survival in 43 populations and 6 regional groupings of blue spruce populations in an eastern Nebraska test

Source of variation	Chi-square analysis df	X^2
(A) Among populations	42	94.5*
Among segments	2	80.8*
Within segment A (25-35%)	2	0.5
Within segment B (45-70%)	21	10.5
Within segment C (75-90%)	17	3.8
(B) Among populations	42	94.5*
Among regions	5	13.7*
Within region I (Wyoming, No. Utah)	5	26.3*
II (No. Colorado)	4	2.6
III (Cen. Utah)	6	7.8
IV (Cen. Colorado)	9	11.0
V (So. Colorado, No. Arizona, No. New Mexico)	9	31.0*
VI (So. Arizona, So. New mexico)	4	2.1

Denotes significance at the 5% level of probability

owest surviving segments being considered homogene- us and separate. Populations 18, 29, and 34 comprised he lowest surviving segment, and populations 4, 6, 7, 8, 1, 12, 13, 16, 21, 24, 26, 27, 31, 32, 35, 38, 50, and 55 omprised the highest surviving segment (fig. 2, table 1). urvival was only weakly correlated with latitude (r = .38).

A partitioning of the 43 populations into six regional roups suggested a trend of higher survival percentages n the northern (I and II) and westernmost (III) groups able 1). Average survival percentages ranged from 77% n group III (central Utah) to 60% in group V (southern olorado, northern Arizona and northern New Mexico. hi-square analysis indicated significant differences mong the regional group means, but also attributed uch of the variation to individual populations within the roups (table 2B).

leight and Vigor

After two field seasons (in 1975), the seedlings aver- ged 30.8 cm in height, with a range of 23.2 to 52.4 cm. ix of the 10 tallest populations (27, 31, 53, 57, 62, and 4) were from southwestern Colorado, Arizona, and lew Mexico (fig. 2). The remaining 4 populations (10, 20, 0, and 55) were from mid-latitude locations in central olorado and central Utah. These 10 populations have naintained their height superiority throughout the -year field test period, and were among the tallest 20 opulations in 1981 (table 3 and fig. 3). The four curves n figure 3 illustrate the pattern of height development of roups of populations with statistically similar heights.

The 11 shortest populations at age 2 in the field (1975) ccurred from northeast Utah and northern Colorado to orthcentral New Mexico. By 1981, however, the most ortherly of these shortest populations had separated nto a significantly taller southern group (17, 18, and 29) nd a significantly shorter northern group (23, 65, 16, 30, 36, 5, 38, and 34) (figs. 2 and 3). This latter group of 8 populations were the shortest 8 populations at age 9 in 1981 (table 3).

Analysis of tree height revealed significant differences among the populations, separating a relatively tall group of mid-latitude (10, 40, and 55) and southern-latitude (9, 17, 27, 28, 39, and 53) (table 3). Populations 64, 31, and 62 were taller than all others, however. The relationship between tree height and latitude, was relatively weak (r = 0.30).

Analysis of the six regional groups showed significant separation among the groups, with trees from southern Arizona and southern New Mexico being significantly taller than trees from Wyoming, Utah, northern and central Colorado (table 4).

Several Arizona and New Mexico populations (9, 17, 31, 39, 53, 62, and 64) were among the most vigorous, although only slightly more so than a series of central and southern Colorado populations (10, 27, 28, and 40) (table 3). Tree vigor, not surprisingly, was strongly correlated with tree height (r = 0.92). A similar north and west to south trend of increasing tree vigor was reflected in the regional groups with regional populations from southern Colorado, Arizona, and New Mexico being the most vigorous (table 4). The southern population 57, within regional groups VI, is an exception (table 3).

Crown Diameter

Tree crowns were wider in some populations from southern Colorado (27 and 28), Arizona (31 and 64), New Mexico (9, 53, and 62), central and northern Colorado (10, and 40), and central Utah (55) (table 3). Width of crowns was also strongly correlated with tree height (r = 0.82), but weakly related to latitude (r = 0.27) and longitude (r = 0.01).

A north-south but nonsignificant trend of increasing crown width was present in the regional groups (table 4).

Frost Injury

Six populations, four of southern origin (27, 36, 57, and 58), were identified as more susceptible to frost injury (table 3); but the relationships among frost injury resulting from early flushing, and latitude and longitude were weak. Analysis of frost injury on the regional basis showed real differences in susceptibility; but although the more northerly regional populations were less susceptible to winter injury, there was no regular pattern (table 4).

Table 3.—Mean data and cluster analysis groupings of means[1] for height, vigor, crown diameter, frost injury, and foliage color of 43 blue spruce populations in an eastern Nebraska test

	Characteristics				
Pop. ID	Height	Vigor	Crown diameter	Frost injury	Foliage color
	m	*no.*	*m*	*no.*	*no.*
34	1.0 a	0.5 a	0.8 a	1.4 b	2.0 a
38	1.2 a	0.6 a	1.0 b	1.4 b	3.4 b
5	1.2 a	0.6 a	1.1 b	1.6 b	6.1 c
36	1.2 a	0.6 a	1.1 b	2.2 c	4.4 b
30	1.3 a	0.6 a	1.0 b	1.7 b	4.5 b
16	1.3 a	0.7 a	1.1 b	1.7 b	4.0 b
65	1.3 a	0.6 a	1.1 b	1.6 b	2.2 a
23	1.3 a	0.7 a	1.0 b	1.7 b	4.0 b
11	1.3 a	0.6 a	1.2 c	1.8 b	3.0 b
25	1.4 a	0.6 a	1.1 b	1.3 a	3.8 b
7	1.4 a	0.6 a	1.1 b	1.7 b	1.9 a
15	1.4 a	0.7 a	1.1 b	1.7 b	3.4 b
32	1.4 a	0.6 a	1.1 b	1.4 b	2.2 a
12	1.4 b	0.7 a	1.1 c	1.3 a	4.2 b
24	1.4 b	0.7 a	1.2 c	1.8 b	4.6 b
35	1.4 b	0.8 b	1.1 c	2.0 c	5.1 c
1	1.4 b	0.7 a	1.2 c	1.5 b	4.1 b
18	1.4 b	0.7 b	1.2 c	1.7 b	5.1 c
21	1.4 b	0.7 b	1.2 c	1.8 b	2.2 a
4	1.5 b	0.7 a	1.2 c	1.2 a	3.1 b
29	1.5 b	0.8 b	1.2 c	1.8 b	6.0 c
37	1.5 b	0.7 a	1.3 c	1.8 b	3.8 b
26	1.5 b	0.7 a	1.2 c	1.4 b	3.2 b
13	1.5 b	0.7 b	1.2 c	1.1 a	2.3 a
57	1.5 b	0.6 a	1.0 b	1.9 c	5.7 c
14	1.5 b	0.8 b	1.2 c	1.8 b	2.8 b
50	1.5 b	0.7 b	1.2 c	1.5 b	3.5 b
8	1.5 b	0.8 b	1.2 c	1.6 b	2.9 b
58	1.6 b	0.7 b	1.2 c	2.0 c	5.7 c
20	1.6 b	0.8 b	1.2 c	2.1 c	3.6 b
6	1.6 b	0.7 b	1.3 c	1.5 b	3.4 b
39	1.6 c	0.8 c	1.3 c	1.5 b	4.2 b
28	1.6 c	0.8 c	1.5 d	1.6 b	4.5 b
17	1.7 c	0.9 c	1.3 c	1.3 a	5.3 c
10	1.7 c	0.8 c	1.4 d	1.6 b	5.5 c
9	1.7 c	0.8 c	1.5 d	1.7 b	6.5 c
55	1.7 c	0.7 b	1.6 d	1.1 a	4.1 b
27	1.7 c	0.8 c	1.5 d	2.1 c	7.1 c
40	1.7 c	0.8 c	1.4 d	1.4 b	4.0 b
53	1.7 c	0.9 c	1.5 d	1.9 b	7.1 c
64	1.9 d	0.9 c	1.4 d	1.3 a	4.8 c
62	1.9 d	0.9 c	1.6 d	1.1 a	1.0 a
31	2.1 d	1.0 c	1.6 d	1.6 b	3.4 b

[1] *Means without a letter in common are different at the 5% level according to the Cluster Analysis Method for Grouping Means in the Analysis of Variance (Scott and Knott 1974). Means of equal value may be separated due to rounding off.*

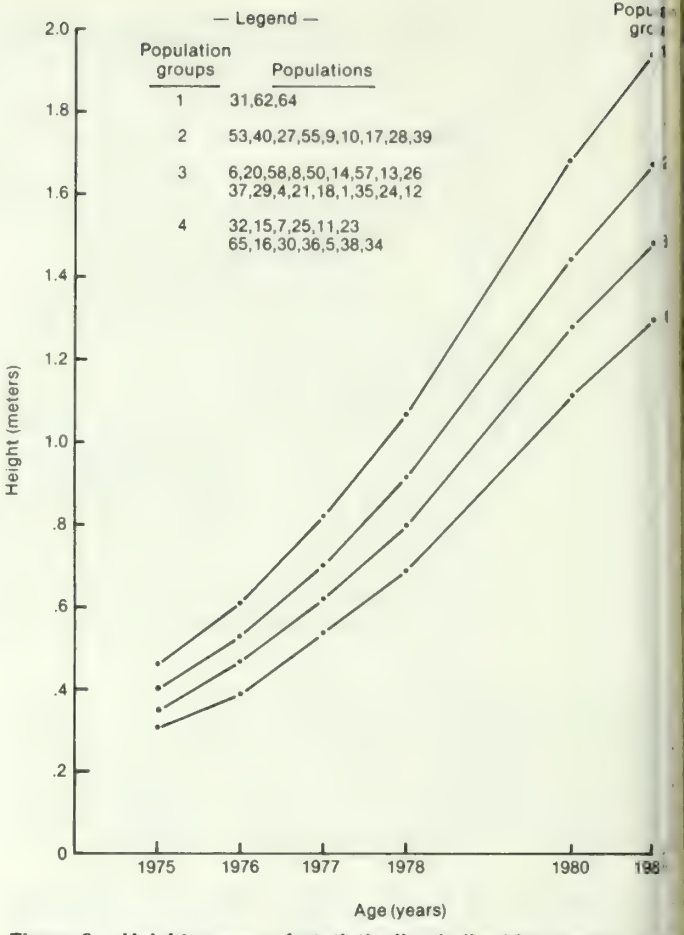


Figure 3.—Height curves of statistically similar blue spruce populations in an eastern Nebraska plantation. (See Table 3 for individual population mean heights and levels of significance.)

Foliage Color

Twelve populations were identified as exhibiting bluer foliage color than others (table 3). Ten of these (17, 18, 27, 29, 35, 53, 57, 58, and 64) were from the southern half of the blue spruce range; populations and 10 were from central and northcentral Colorado (fig. 2). Although the relationship between foliage color and latitude was weak (r = 0.20), there was significant separation among the regional groups with a pattern of increasing blueness toward the southern portions of the range, especially in group V (southern Colorado, northern Arizona, and northern New Mexico) (table 4).

Discussion

Although survival varied considerably among the populations, a multiple comparison analysis did not reveal any statistically pairwise differences. This was attributed to a condition common to many population, seed source, provenance, and progeny tests; i.e., large numbers of entries with relatively small sample size per entry. However, the data were partitioned into components according to differences among population group means and to differences within each group, and the populations were separated into three groups, o

Table 4.—Mean data and multiple range tests[1] for height, vigor, crown diameter, frost injury, and foliage color of 6 regional groupings of 43 blue spruce populations in eastern Nebraska test

Characteristics									
Height		Vigor		Crown diameter		Frost injury		Foliage color	
m		*no.*		*m*		*no.*		*no.*	
I[2]	1.25 a	I	0.66 a	II	1.13 a	I	1.37 a	I	3.0 a
II	1.40 a	III	0.66 a	I	1.16 a	III	1.45 a	II	3.7 a
III	1.43 a	II	0.67 a	III	1.19 a	II	1.63 a-b	III	3.7 a
IV	1.49 a	IV	0.72 a-b	IV	1.19 a	VI	1.69 a-b	IV	3.9 a
V	1.58 a-b	V	0.79 b	V	1.31 a	V	1.75 b	VI	4.5 a-b
VI	1.77 b	VI	0.79 b	VI	1.37 a	IV	1.77 b	V	5.4 b

[1]*Means followed by a common letter are not different at the 5% level (Tukey's Multiple Range Analysis of Pairwise Differences).*

[2] *I = Wyoming and northern Utah*
II = Northern Colorado
III = Central Utah
IV = Central Colorado
V = Southern Colorado, northern Arizona, and northern New Mexico
VI = Southern Arizona and southern New Mexico

hich the lowest and highest surviving groups were onsidered separate and homogeneous. There were also fferences among regional group means; but no clear ographic pattern in survival was apparent.

There were important differences among the 43 popu-lions for the other 5 evaluation criteria. Correlation of ese characteristics with the geographic variables of itude and longitude was generally weak, however, flecting considerable variability among the popula-ns throughout the range of the species.

Partitioning the 43 populations into the six regional oups indicated significant differences among the oups and revealed a series of directional trends in aracteristic expression. These trends point to some-hat higher survival in the northern populations, and ater height growth and vigor, more frost injury, and er foliage color in the southern populations. The in-nsistencies between height and vigor, especially in pulations 17, 29, 35, 55, and 57, may indicate popula-ns whose performances may change drastically in the ure (table 3).

Dawson and Rudolf (1966) tested seven blue spruce d lots collected from stands in Wyoming, Utah, Colo-lo, Arizona, at Denbigh, North Dakota. They reported t at age 13 (5 years in the field), a source from the Wyoming-Utah border exceeded the other six sources in rvival, height growth, resistance to frost damage, and wn diameter. Although statistically significant differ-es among populations were few in this analysis, col-tion of seed from the best stands throughout Colorado d Utah would seem advisable for use in the northern eat Plains and the Canadian Prairie Provinces, where nter injury to southern origins of blue spruce may be ely. Cram (1968) reported that blueness of foliage lor was transmittable to as many as 50% of the geny of some locally grown blue spruce trees in Skatchewan, Canada.

Conclusions

With minor variations, the data reported here confirm the developmental patterns reported by Hanover and Reicosky (1972), Bongarten (1978) and Canada Department of Regional Economic Development (1979). These data show that populations in the southern portion of the species range tend to have trees exhibiting more of the characteristics commonly desired in the species; e.g., faster growth and more blueness in foliage color. Individual populations within regions are quite variable, however, making regions of limited value in specifying where better seed can be collected. The probability of locating trees, exhibiting desirable characteristics for Great Plains plantings, would appear to be increased by selecting within stands containing high percentages of desirable phenotypes in southern Colorado, Arizona, and New Mexico.

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APPENDIX

Table A-1.—Assignment of qualitative identifications to blue spruce foliage color, after Ridgway (1912)

Rating number	Color name	Plate number	Color or Hue number	Tone
0	Courge Green	XVII	25′	i
1	Parrot Green	VI	31	k
2	Chromium Green	XXXII	31′′	i
3	Deep Dull Yellow Green (1)	XXXII	31′′	k
4	Grass Green	VI	33	k
5	Pois Green	XLI	29′′′	i
6	Pistachio Green	XLI	33′′′	-
7	Gnaphalium Green	XLVII	29′′′′	d
8	Deep Bluish Glaucous	XLII	37′′′	d

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Van Haverbeke, David F. 1984. Genetic variation in blue spruce: A test of populations in Nebraska. USDA Forest Service Research Paper RM-253, 6 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Analyses of 43 blue spruce populations at age 12 (9 years in the field) revealed significant differences among populations for survival, height, vigor, crown diameter, frost injury, and foliage color. Use of regions increases the probability of locating better seeds sources, but high variability among individual populations within regions limits their value in specifying where better seed sources can be collected. Phenotypes should be selected in best stands within regions.

Keywords: *Picea pungens*, provenance test, geographic variation

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Rocky Mountains

Southwest

Great Plains

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Rocky Mountain Forest and Range Experiment Station

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Rocky Mountain
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Research Paper
RI-254

Natural Regeneration of Engelmann Spruce after Clearcutting in the Central Rocky Mountains in Relation to Environmental Factors

Robert R. Alexander

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Abstract

Successful natural regeneration of Engelmann spruce in small clearcut openings depends on weather and aspect and is modified by cultural treatments. Small clearcut openings (1–2 ha) can be successfully regenerated on north aspects with mineral soil seedbeds and shade. On south aspects, shade is absolutely essential for any survival. However, successful natural regeneration is not likely regardless of cultural treatments. Drought is the most serious cause of mortality; but clipping by birds, frost heaving (north aspect), heat girdle (south aspect), and snowmold (north aspect) caused significant losses.

Cover Photo.—The 1969 replication of seedbed treatments on the north aspect, Fraser Experimental Forest, Colorado.

SDA Forest Service
Research Paper RM-254

May 1984

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Natural Regeneration of Engelmann Spruce after Clearcutting in the Central Rocky Mountains in Relation to Environmental Factors

Robert R. Alexander

The uncertainty of successful Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.) natural regeneration after clearcutting spruce-subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) forests is a major management concern in the central Rocky Mountains (Alexander 1974). Three basic requirements for natural regeneration success are: (1) an adequate supply of seed, (2) a suitable seedbed, and (3) an environment compatible with germination and survival (Roe et al. 1970). Research and observations most often identified environmental factors as the most limiting to Engelmann spruce natural regeneration success (Noble and Alexander 1977). This study, started in 1968, was designed to identify limiting factors and determine modifications in cultural practices needed to provide suitable environments for spruce regeneration. This paper includes data from 1973 through 1982, and from a published 5-year progress report (Noble and Alexander 1977).

STUDY AREAS

Field observations were made from 1968 through 1982, on the Fraser Experimental Forest, in central Colorado, on two areas approximately 7.2 km apart. Both study areas are at about 3,230 m elevation—one on a north aspect and the other on a south aspect. Slope is 10–12% on the north aspect and 12–15% on the south aspect. Both study areas are enclosed within 30.5- × 33-m hardware cloth rodent exclosures (Noble and Alexander 1975) in the center of 1.46-ha-square clearcut openings (fig. 1). The opening on the north aspect was cut in 1956, the south aspect in 1967. The hardware cloth generally excluded deer mice (*Peromyscus manicula*tus Wagner), red-backed voles (*Clethrionomys gapperi* Vigors), mountain voles (*Microtus montanus* Peale), western chipmunks (*Eutamias minimus* Bachman), and pine squirrels (*Tamiasciurus hudsonicus fremonti* Audubon and Bachman); but not pocket gophers (*Thomomys talpoides* Richardson) or birds that feed on tree seed, such as the grey-headed junco (*Junco caniceps* Woodhouse) (Noble and Shepperd 1973). Additional control of rodent populations was initially obtained by poisoning; one tablespoon of 1080-treated oats or gophicide treated wheat was placed in a bait can with an opening one large enough to allow access to small mammals. Bait cans were placed on a 15.2- × 15.2-m grid across the clearcut openings. Poisoning was discontinued after 1973, when the U.S. Environmental Protection Agency prohibited the use of rodenticides. Trapping was used thereafter to control small mammals.

The original stands were spruce-fir or mixed spruce-fir and lodgepole pine (*Pinus contorta* Dougl. ex Loud.),

Figure 1.—Study area on the north aspect, after rodent exclosures were installed, but before seedbed treatments were in place.

typical of the forests on the west side of the Continental Divide. These old-growth stands were situated on sites of moderate productivity (site index 60 to 70) (Alexander 1967). The habitat type is *Abies lasiocarpa/Vaccinium scoparium*, the most common spruce-fir habitat type in Colorado. The *Vaccinium* union does not compete as severely with tree seedlings as undergrowth vegetation does in other habitat types.

The climate of the Fraser Experimental Forest is also typical, and can be characterized as cold and humid (Haeffner 1971). Mean annual temperature is 0.6° C with extremes of −40° C and +32° C. Annual precipitation averages 58 cm, with a range of 46 to 86 cm. Approximately two-thirds of the precipitation falls as snow from October through May.

Soils on both areas are gravelly, sandy loams developed in place from coarse-textured material weathered from mixed gneisses and schists (Retzer 1962). Average depth to the C horizon is 30–40 cm on the north aspect and 50 to 60 cm on the south aspect. Laboratory analyses of the soils showed the following texture composition and soil moisture content, respectively (Noble 1972):

	North aspect (%)	South aspect (%)
Sand	56	54
Silt	34	30
Clay	10	16
1/3 bar tension	18	15
15 bar tension	9	8

METHODS

Experimental Design

The design was a two-by-two factorial replicated over 10 years, in randomized blocks. A set of twelve 1-m^2 seedbeds (four seedbed treatments replicated three times) was prepared on each aspect, each year from 1968 through 1977.

Seedbed Treatments

The four seedbed treatments were scarified-shaded, scarified-unshaded, unscarified-shaded, and unscarified-unshaded. Plots were scarified by hand to remove all material to mineral soil. Scarification simulated scalping with a dozer blade. Overhead shade was provided by wooden frames made from 5-cm-wide furring strips alternated with 5-cm spaces, elevated 20 to 25 cm above the ground on metal framing. Slots of the shade frames were oriented in a north-south direction to provide alternate periods of shade and sunlight (fig. 2).

Seeding

The Engelmann spruce seed used in this study was collected on the Fraser Experimental Forest. New collections were made only when stored seed viability, based on laboratory germination tests, dropped to less than 60%. In late September of each year (1968 to 1977), an estimated 125 viable seeds were evenly broadcast on each seedbed. The total number of seeds sown per seedbed each year varied from 165 to 210, depending on viability. The seeds were not covered, because the intent was to simulate natural regeneration. The number of seeds sown corresponds to 1,235,000 sound seeds per hectare, which can be expected from a heavy natural seedfall (Alexander et al. 1982). Plots we placed at least 45 m from the nearest timber edge minimize the input of seed from adjacent timber stand

Figure 2.—Shade frame in place on north aspect scarified-shaded treatment.

Environmental Measurements

Air temperatures and relative humidity were r corded from June to October each year, on each aspec using hygrothermographs and maximum-minimum the mometers housed in standard Weather Bureau shelte (fig. 3). Periodically, air temperatures also were mea ured in full sunlight at the standard height of 1.37 n using temperature thermistors and a circuit bridg Wind velocity at 1.83 m was measured with recordin anemometers; precipitation was measured gravimetr cally with 20.3-cm raingages exposed without funnels c tubes.

Total horizontal incident radiation was obtained fro a pyroheliometer located in a level opening between th two aspects but at a slightly lower elevation. These dat were adjusted for slope and aspect using equation developed by Kaufmann and Weatherred (1982) to ob tain potential direct beam solar irradiation, expresse as total langleys (ly) per day.

Periodically, seedbed temperatures were measure from mid-June to mid-August in 1971, 1972, and 1973, a the surface with an infrared field thermometer, and a 2.5, 5.1, 10.2, and 20.3 cm above and below the surface with thermistors (fig. 4). No measurements were mad within 48 hours following 5.1 cm or more of precipita tion to avoid variability in temperatures associated wit evaporation. Data from 18 days when air temperature were near the average maximum were used in the fina tabulation. Absolute temperatures at the surface wer estimated using temperature-sensitive wax tempules.

Seedling Measurements

During the first growing season after each sowing germination, survival, and cause of mortality were re corded at least twice weekly; after the first season, sur vival and mortality counts were made weekly. Measure ments were begun in June, when the plots were firs clear of snow, and ended in October, with the onset o winter snow cover.

Data Compilation and Analysis

Environmental

To characterize the environment on each aspect measurements of bulk-air temperatures, precipitation net incident radiation, and wind velocity were compiled into daily, weekly, monthly, and seasonal summaries. Similar compilations were made for vapor pressure deficits (VPD) computed from relative humidities and temperatures. Precipitation and temperature also were compared with long-term weather records reported by

Haeffner (1971) for the Fraser Experimental Headquarters site at 2,743 m elevation, and approximately 7.2 km from each study site.

Soil surface and subsurface, soil profile, and air profile temperatures were summarized to characterize the microenvironment associated with seedbeds so that comparisons could be made between seedbed treatments for each aspect. Soil surface temperatures and subsurface-soil and air-temperature profiles were averaged to provide estimates of mean maximum diurnal temperatures.

eedlings

Differences in germination each year for the 10 years of record were tested separately for each aspect by analysis of variance after arc-sin transformation. Seedbed treatments and years were the independent variables; percent germination each year the dependent variable. Orthogonal comparisons were made between treatments. The sampling unit was the individual plot total.

Differences in survival also were tested for each aspect using analysis of variance after arc-sin transformation. Seedbed treatments and years were the independent variables. The dependent variable was the percent of surviving seedlings at the end of 1 year, 5 years, and the end of the study.

RESULTS

Weather Factors

r Temperature

Mean air temperature recorded in the weather shelters on both aspects was near normal for the 14 years of observation, varying less than 1° C from the long-term average (8.3° C) on the Fraser Experimental Forest. Temperature patterns for the months of June through October were similar on both aspects (fig. 5). Although mean temperatures during the period of observation varied about 3° C between years on both aspects, the south aspect averaged only about 1° to 1.5° C warmer than the north aspect (table 1).[2]

This temperature difference and pattern occurred whether measured in the standard shelters or in the open at 1.37 m. Temperatures in the open were generally 1° C cooler at sunrise, 3–4° C warmer at noon, and about the same at sunset as was measured in the shelters.

Figure 3.—Standard weather shelter installed on the north aspect showing hygrothermograph and max-min thermometer. Standard precipitation can is being weighed. Cup anemometer and generator in place (recorder not shown).

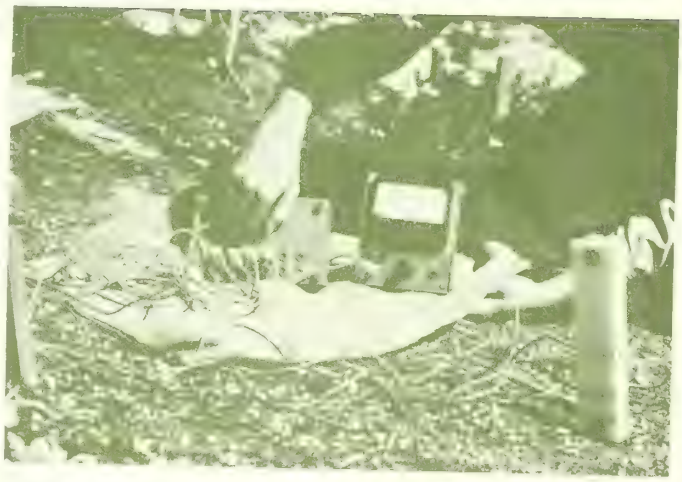

Figure 4.—Simultaneous air-temperature profiles were measured with unshielded thermistors at 2.5, 5.1, 10.2, and 20.3 cm above the surface using a tele-thermometer and switchbox.

Precipitation

Mean precipitation on both aspects was also near normal for June through October, varying less than 2 cm from the long-term average (23 cm) on the Fraser Experimental Forest. Precipitation patterns were similar on each aspect; but there was considerable variability from year to year (fig. 6). The south aspect averaged about 2 to 6 cm more precipitation than the north aspect during the months of June through October (table 1).[2]

Vapor Pressure Deficits (VPD)

VPD followed similar patterns on both aspects; but there was also considerable variability from year to year (fig. 7). Mean VPD was always slightly higher (0.5–

[2]*Mean hourly maximum, minimum, and mean air temperatures, mean monthly precipitation, average daily maximum, minimum, and mean vapor pressure deficits, net radiation, and mean daily and peak gust wind velocity are given in tables A-1 through A-5, for the months of June through October, on each aspect, for the years 1968 through 1982.*

Table 1.—Average maximum, minimum and mean for the five weather factors measured June through October

	North Aspect			South Aspect		
	max.	min.	mean	max.	min.	mean
Air temperature (° C)	14.1	1.6	7.6	14.8	3.2	8.4
Precipitation (cm)	28.6	6.4	21.9	34.4	8.6	25.0
Vapor pressure deficit (mm Hg)	12.0	5.0	8.8	12.9	5.5	9.5
Net radiation (ly/day)	554	406	480	600	446	526
Wind (km/hr)	7.2	—	2.6	10.6	—	3.3

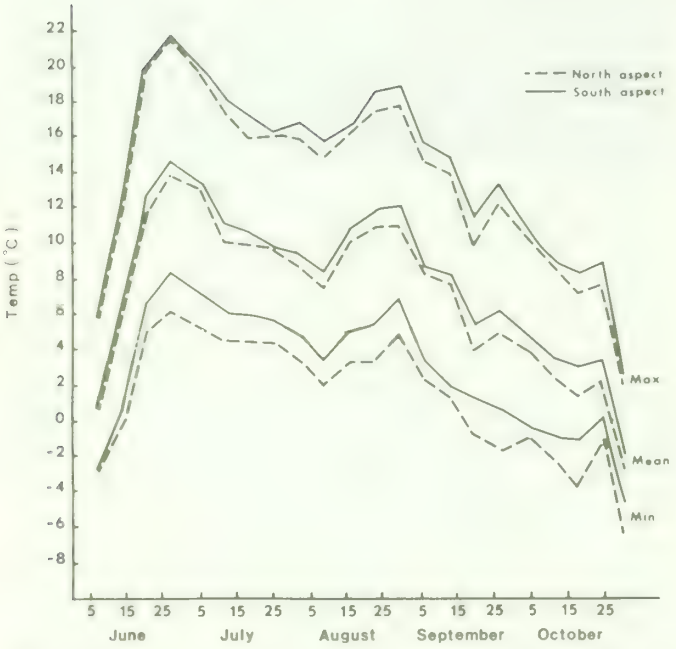

Figure 5.—Comparison of bulk-air temperatures recorded in weather shelters for the 1974 season illustrated characteristic season pattern between north and south aspects.

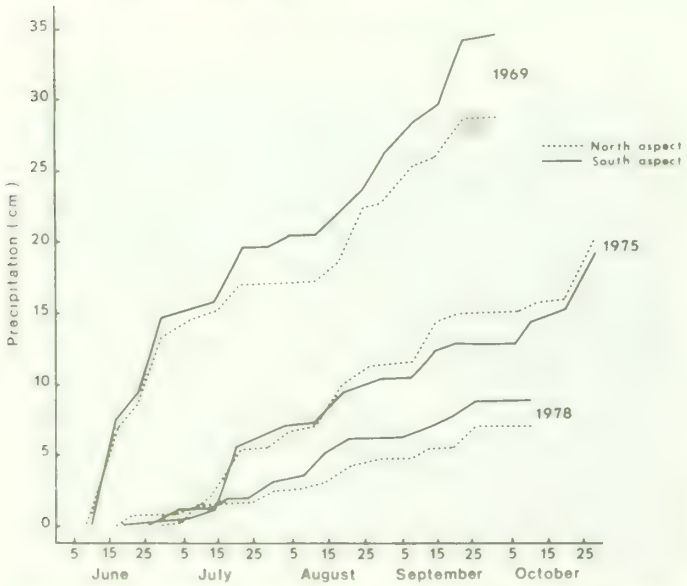

Figure 6.—Seasonal precipitation patterns for above average, average, and below average years on the north and south aspects.

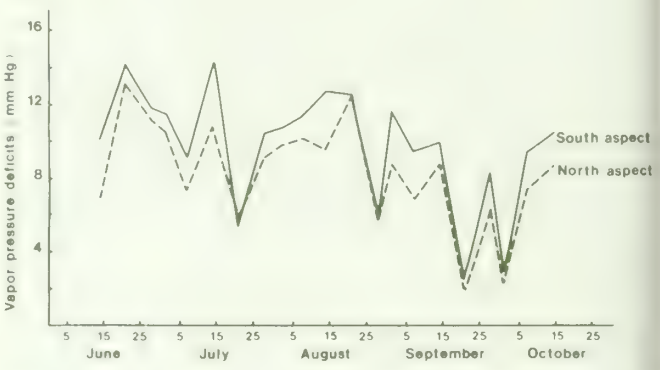

Figure 7.—Comparison of vapor pressure deficits for the 197 season illustrates the characteristic seasonal pattern betwee north and south aspects.

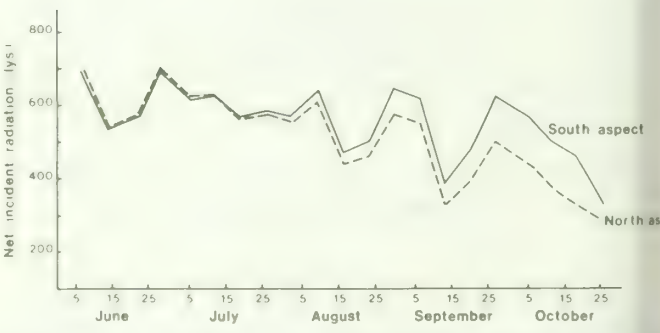

Figure 8.—Comparison of net incident radiation for the 1975 season illustrates the characteristic seasonal pattern between north and south aspects.

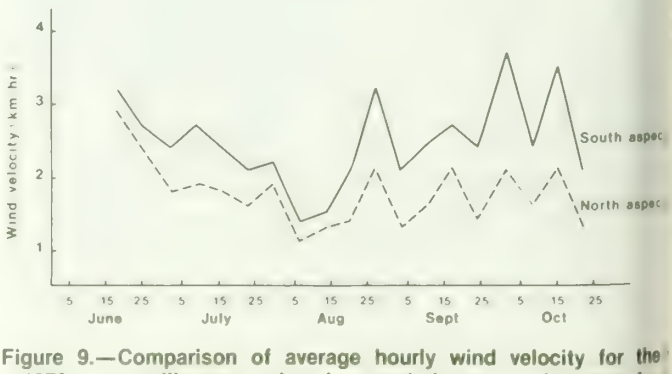

Figure 9.—Comparison of average hourly wind velocity for the 1979 season illustrates the characteristic seasonal pattern between north and south aspects.

1.0 mm Hg) on the south aspect (table 1).[2] The monthly average VPD was generally highest in July and lowest in October.

Net Incident Radiation

The south slope received about 9% more net incident radiation per growing season, averaging 46 ly per day more than on the north aspect or accumulating 6,762 ly more during the months of June through October. The highest daily average was for June on the north aspect; thereafter, the radiation decreased, particularly on the north aspect (fig. 8). Maximum average daily growing season radiation was in June 1971 on the north aspect (781 ly) and the minimum (127 ly) in October of 1974 on the north aspect (table 1).[2]

Wind Velocity

Both aspects were well ventilated and wind patterns were similar (fig. 9); but average wind velocity and peak gusts were higher on the south aspect, especially in late summer and fall (table 1).[2] The wind data also indicated a typical mountainous wind pattern—a slow downslope cold-air drainage during the night, with a morning upslope reversal, generally followed by gusty afternoon winds.

Seedbed Temperatures

Surface temperatures were affected by seedbed type, shade and aspect (table 2). Unshaded duff surfaces had the highest temperatures on both aspects. Average maximum surface temperatures on the south aspect reached 60° C by 10 a.m. (MST) and were above the scale of the instrument until about 3 p.m. Temperature sensitive wax tempules indicated absolute maximums between 79° and 83° C. On the north aspect, average unshaded duff surface temperatures reached 53° C by 11 a.m., occasionally exceeded the range of the instrument, but averaged about 55° C until 2 p.m. Absolute maximum temperatures were between 63° and 73° C. Average maximum surface temperatures for unshaded mineral soil on both aspects were at least 12° C cooler than unshaded duff surfaces.

Shade reduced maximum surface temperatures 6–8° C on both aspects (table 2). Furthermore, shaded duff surfaces on the north aspect were 2° C cooler than on the south aspect, and shaded-mineral soil surfaces were about 12° C cooler.

Air profile temperatures near the surface were affected more by shade than by height above the surface, seedbed type, or aspect (table 2). Shade reduced maximum temperatures 6–10° C and produced more uniform temperatures with height. Air temperatures were higher near the surface (2.5 cm) and decreased with an in-

Table 2.—Profile of mean, maximum and minimum temperatures (°C) of seedbeds by aspect at the surface, and at different heights above and below the surface[1]

Location	Height (cm)	Scarified-Shaded			Scarified-Unshaded			Unscarified-Shaded			Unscarified-Unshaded		
		mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.
North Aspect													
Above surface	20.3	19.3	10.8	23.6	22.4	9.4	30.0	18.3	9.4	22.2	24.1	13.3	31.7
	10.2	19.5	10.8	23.9	22.9	9.4	30.6	18.1	9.4	21.7	24.4	13.3	31.7
	5.1	19.6	10.8	23.9	24.0	10.0	31.7	18.4	9.4	22.8	26.3	12.5	33.1
	2.5	20.4	10.8	25.9	25.2	10.6	33.3	19.0	10.0	25.0	28.1	13.6	35.3
Surface	U[2]	29.7	13.9	39.0	33.7	18.3	43.0	39.2	18.9	48.9	42.3	19.4	55.0
	S[2]	24.3	12.2	31.1	—	—	—	33.2	13.9	42.7	—	—	—
Below surface	2.5	17.3	11.1	21.1	18.7	11.1	24.8	15.1	11.4	19.7	21.3	15.6	25.3
	5.1	15.8	11.1	17.8	17.6	10.6	22.2	12.9	10.9	15.9	18.2	12.8	21.1
	10.2	13.8	11.1	15.0	14.9	10.6	17.5	12.0	9.7	13.1	15.2	11.1	17.2
	20.3	11.7	10.0	12.8	13.5	10.6	15.6	10.4	9.4	11.1	12.8	11.1	13.6
South Aspect													
Above surface	20.3	18.6	13.3	23.3	22.8	13.1	28.9	18.3	10.9	22.8	22.7	13.6	29.4
	10.2	18.4	13.3	22.5	23.5	12.8	29.4	18.5	10.9	23.3	23.3	13.6	30.0
	5.1	18.7	13.3	22.8	24.6	13.1	30.6	19.0	11.1	24.7	24.7	14.4	32.0
	2.5	20.0	12.8	24.4	26.0	13.6	32.5	19.7	11.1	25.9	26.2	15.0	33.9
Surface	U[2]	39.1	19.4	50.0	41.9	21.7	51.0	41.8	16.1	51.1	[3]>51.4	21.1	[3]>60.0
	S[2]	33.7	16.4	43.3	—	—	—	34.5	13.6	43.5	—	—	—
Below surface	2.5	19.3	12.8	23.6	23.7	15.0	29.4	17.1	11.7	20.3	22.8	13.6	26.4
	5.1	17.7	12.2	21.1	20.7	13.6	25.6	14.2	11.4	17.0	19.0	12.2	22.2
	10.2	15.3	11.7	17.2	17.6	11.7	21.1	12.6	10.6	13.9	15.6	11.7	17.2
	20.3	13.4	11.7	15.0	13.7	11.7	16.7	11.8	10.3	13.3	13.4	11.7	14.2

[1]*Measurements made hourly from 6 a.m. to 7 p.m., between June 15 and August 15, 1971, 1972 and 1973.*
[2]*U = Unshaded, S = Shaded.*
[3]*Maximum surface temperatures on unscarified-unshaded seedbeds exceed the range (60° C) of the instrument being used.*

crease in height to 20.3 cm. There was one seeming anomaly; air profile temperatures were generally 1–2° C higher on the north aspect.

Soil profile temperatures just below the surface were affected more by shade and depth below the surface than seedbed type and aspect (table 2). Shade reduced maximum temperatures near the surface (2.5 cm) 4° to 6° C, but was less effective as depth increased to 20.3 cm, where maximum soil temperature differences between shaded and unshaded seedbeds were 1° to 3° C. Soil profile temperatures were only slightly higher on the south aspect. Soil temperatures decreased considerably (8–12° C) as depth increased from 2.5 to 20.3 cm on both aspects.

Seedling Establishment

Germination

Germination was considerably better on the north aspect than on the south aspect (table 3). However, total germination on the north aspect for all years was only 6.1%, ranging from a high of 10.5% in 1974 to a low of 0.9% in 1971 (table 3). Germination was improved significantly in most years by scarification but not by shade. The scarification × years interaction was highly significant, indicating that there was considerable variability in germination from year to year on scarified seedbeds.

Total germination for all years on the south aspect was only 2.9%, ranging from a high of 14.5% in 1972 to a low of 0.2% in 1970 (table 3). In some years, shade significantly improved germination, and in a few years, the combination of shade and scarification significantly improved germination. All interactions between years and cultural treatments were highly significant, indicating high variability in germination among the treatments from year to year.

Survival

Survival was also better on the north aspect than on the south aspect (table 3). However total survival on the north aspect at the end of the study was only 1.4% of the viable seeds sown. Seedlings that survived through the fifth growing season generally survived to the end of the study. In most years, survival was significantly improved by scarification, by shade, and by the combination of scarification and shade. The scarification × years interaction and the differences in survival between years were also significant.

On the south aspect, total survival was only 0.2% of the viable seeds sown (table 3). Although seedlings that

Table 3.—Percent germination and survival of Engelmann spruce by aspect, seedbed treatment and year (basis number of viable seeds sown)

Year	Scarified and Shaded				Scarified and Unshaded				Unscarified and Shaded				Unscarified and Unshaded				Total			
	Germination	Survival end of-			Germination	Survival end of-			Germination	Survival end of-			Germination	Survival end of-			Germination	Survival end of-		
		1st yr	5th yr	study[1]		1st yr	5th yr	study[1]		1st yr	5th yr	study[1]		1st yr	5th yr	study[1]		1st yr	5th yr	study[1]
	North Aspect																			
1969	21.1	10.9	7.5	6.9	12.8	7.2	3.2	3.2	4.5	1.6	1.3	0.8	0.8	0	0	0	9.8	4.9	3.0	2.7
1970	12.5	8.8	4.5	4.3	7.2	4.3	1.6	1.6	4.5	2.1	0.3	0.3	1.3	0.5	0.5	0.5	6.4	3.9	1.8	1.7
1971	1.1	0.5	0.5	0.5	2.1	2.1	0.5	0.5	0	0	0	0	0.5	0.3	0	0	0.9	0.7	0.3	0.3
1972	6.9	1.3	0.8	0.8	11.2	0.8	0	0	1.6	0.3	0	0	2.4	0.3	0	0	5.5	0.7	0.2	0.2
1973	7.2	4.0	2.1	2.1	3.5	1.3	0.3	0.3	9.6	5.9	3.5	2.9	3.2	1.9	0	0	5.9	3.3	1.5	1.3
1974	8.0	5.9	2.9	2.7	2.1	1.1	0.3	0.3	21.1	4.5	2.4	2.1	10.9	2.1	0.5	0.5	10.5	3.4	1.5	1.4
1975	9.3	3.7	0.5	0.5	8.3	3.7	0.5	0.5	4.8	2.9	1.6	1.3	1.1	0.5	0	0	5.9	2.7	0.7	0.6
1976	1.6	0.5	0.3	0.3	1.1	0.5	0.3	0.3	8.3	5.9	2.9	2.9	2.1	1.9	1.3	1.3	3.3	2.1	1.2	1.2
1977	10.7	8.3	2.4	2.4	4.8	2.4	0.3	0.3	1.3	1.1	0.3	0.3	1.1	0.5	0	0	4.5	3.1	0.7	0.7
1978	15.2	10.9	9.9	9.9	11.7	7.2	6.1	6.1	4.5	2.9	1.6	1.6	0.3	0	0	0	7.9	5.3	4.4	4.4
Aver.	9.4	5.5	3.1	3.0	6.5	3.1	1.3	1.3	6.0	2.7	1.4	1.2	2.4	0.8	0.2	0.2	6.1	3.0	1.5	1.4
	South Aspect																			
1969	6.7	1.3	0.3	0.3	2.1	0	0	0	6.9	2.4	1.9	1.9	2.4	0	0	0	4.5	0.9	0.5	0.5
1970	0	0	0	0	0	0	0	0	0.8	0.3	0.3	0.3	0	0	0	0	0.2	0.1	0.1	0.1
1971	1.6	0.5	0.5	0.5	1.3	0	0	0	0.3	0	0	0	0.5	0	0	0	0.9	0.1	0.1	0.1
1972	10.9	1.9	0.8	0.8	9.6	0.5	0	0	26.9	1.1	0	0	10.7	0	0	0	14.5	0.9	0.2	0.2
1973	5.9	2.4	1.3	1.3	0	0	0	0	5.9	2.4	1.1	0.5	2.7	1.3	0	0	3.6	1.5	0.6	0.5
1974	0	0	0	0	0	0	0	0	5.6	0.3	0	0	5.1	0	0	0	2.7	0.1	0	0
1975	0.3	0	0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0.3	0	0	0
1976	0.3	0	0	0	0	0	0	0	0.8	0.3	0	0	0	0	0	0	0.3	0.1	0	0
1977	2.7	0.3	0	0	0	0	0	0	4.3	0.3	0	0	0	0	0	0	1.7	0.1	0	0
1978	0.5	0	0	0	0.5	0	0	0	0.5	0	0	0	0	0	0	0	0.4	0	0	0
Aver.	2.9	0.6	0.3	[2]0.3	1.4	0.1	0	0	5.3	0.7	0.3	0.3	2.1	0.1	0	0	2.9	0.4	0.2	0.2

[1]*Seedling age in 1982 ranged from 5-years old (1978 germination) to 14-years old (1968 germination).*
[2]*Seedling age in 1982 ranged from 10-years old (1973 germination) to 14-years old (1969 germination).*

survived through the fifth growing season generally survived to the end of the study, there was no survival on any of the seedbed treatments for seeds sown after 1975. In those few years when seedlings survived beyond the first year, shade and the combination of shade and scarification significantly improved survival. The shade × years interaction was significant, indicating high variability between years.

Mortality

Seventy-six percent of the seedlings that germinated on the north aspect died by the end of the study (table 4). About two-thirds of the total mortality occurred the first year. On the south aspect, 95% of the seedlings were dead by the end of the study, with more than 90% of the total mortality occurring the first year.

Drought was the most significant cause of mortality on both aspects, followed by clipping by birds (table 4). On the north aspect these two factors plus frost heave and snowmold accounted for nearly 90% of the mortality. On the south aspect, drought, clipping, and heat girdle accounted for about 90% of the mortality.

Seed:Seedling Ratios

Seed:seedling ratios developed from this study have been reported previously (Alexander 1983). Therefore, only the necessary detail is repeated here.

The lowest seed:seedling ratios were on the scarified-shaded seedbeds on the north aspect. Neither shade nor scarification was as effective as the combination of shade and scarification on the north aspect. It required nearly 2.5 times as many seeds to produce a 5-year-old seedling on the scarified-unshaded and unscarified-shaded seedbeds as on the scarified-shaded seedbeds. It required nearly 13 times as many seeds on the unscarified-unshaded seedbeds to produce a 5-year-old seedling as on the scarified-shaded seedbeds (table 5).

On the south aspect, the only seed:seedling ratios established were on the scarified-shaded and unscarified-shaded seedbeds. Compared to equivalent seedbeds on the north aspect, it required more than 10 times as many seeds on scarified-shaded seedbeds and nearly 5 times as many on the unscarified-shaded seedbeds to produce a 5-year-old seedling (table 5).

Table 4.—Percent total mortality by aspect, cause and seedbed treatment (basis number of seedlings that germinated)

Cause of Mortality	Scarified-Shaded			Scarified-Unshaded			Unscarified-Shaded			Unscarified-Unshaded			Total		
	End 1st yr	End 5th yr	End study[1]	End 1st yr	End 5th yr	End study	End 1st yr	End 5th yr	End study	End 1st yr	End 5th yr	End study	End 1st yr	End 5th yr	End study
North Aspect															
Drought	9.9	14.2	14.2	8.3	9.9	9.9	15.6	20.2	20.5	7.8	10.4	10.4	41.6	54.7	55.0
Clipping	7.2	7.2	7.2	6.1	6.1	6.1	1.3	1.3	1.3	0	0	0	14.6	14.6	14.6
Frost heave	0.3	6.4	6.4	0.6	4.5	4.5	0.1	0.7	0.7	0	0.5	0.5	1.0	12.1	12.1
Snow mold	0	0.9	1.3	0	2.6	2.6	0	0.7	1.2	0	0	0	0	4.2	5.1
Washout	2.0	2.3	2.3	1.0	1.2	1.2	0	0	0	0	0	0	2.9	3.5	3.5
Freezing	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.7	0.7	0.7	0.7	1.1	1.6	1.6
Heat girdle	0.7	0.7	0.7	0.9	0.9	0.9	0.1	0.1	0.1	0	0	0	1.7	1.7	1.7
Other[2]	0.9	1.9	2.0	1.4	2.5	2.5	0.6	1.8	1.9	0	0	0	2.9	6.2	6.4
Total	21.0	33.7	34.2	18.3	27.8	27.8	18.1	25.5	26.4	8.5	11.6	11.6	65.8	98.6	100.0
South Aspect															
Drought	10.1	11.1	11.1	7.7	7.7	7.7	23.8	26.0	26.5	13.9	14.7	14.7	55.5	59.5	60.0
Clipping	7.0	7.0	7.0	0.5	0.5	0.5	10.8	10.8	10.8	1.2	1.2	1.2	19.5	19.5	19.5
Frost heave	0.5	2.2	2.4	0.5	0.9	0.9	0.5	0.5	0.5	0	0	0	1.5	3.6	3.8
Snow mold	0	0	0	0	0	0	0	0.2	0.2	0	0	0	0	0.2	0.2
Washout	1.2	1.2	1.2	0.7	0.7	0.7	0	0	0	0	0	0	1.9	1.9	1.9
Freezing	0	0.2	0.2	0	0	0	0.5	0.5	0.5	0	0	0	0.5	0.7	0.7
Heat girdle	1.0	1.0	1.0	1.7	1.7	1.7	4.8	4.8	4.8	2.6	2.6	2.6	10.1	10.1	10.1
Other[3]	0.2	0.5	0.5	0.7	0.7	0.7	1.0	1.9	1.9	0.7	0.7	0.7	2.6	3.8	3.8
Total	20.0	23.2	[4]23.5	11.8	12.2	12.2	41.4	44.7	45.2	18.4	19.2	19.2	91.6	99.3	100.0

[1] *Seedlings age at end of study (1982) varied from 5 to 14 years old.*
[2] *Includes isolation, damping off, gophers and unknown.*
[3] *Includes isolation, damping off and unknown.*
[4] *Seedlings age at end of study (1982) varied from 10 to 14 years old.*

Table 5.—Seed to seedling ratios at the end of germination, and the first, and fifth growing seasons by seedbed treatment and aspect (Alexander 1983)

Seedbed treatment	Germinating seedlings			First year survival[1]			Fifth year survival[2]		
	Mean	Range	%	Mean	Range	%	Mean	Range	%
North Aspect									
Scarified shaded	11:1	5:1 to 94:1	9	18:1	9:1 to 188:1	59	32:1	10:1 to 375:1	57
Scarified unshaded	15:1	8:1 to 94:1	6	33:1	14:1 to 188:1	47	76:1	16:1 to ∞	44
Unscarified shaded	17:1	5:1 to [3]∞	6	37:1	17:1 to ∞	45	72:1	29:1 to ∞	52
Unscarified unshaded	42:1	9:1 to 375:1	2	125:1	54:1 to ∞	34	417:1	75:1 to ∞	30
South Aspect									
Scarified shaded	35:1	9:1 to ∞	3	156:1	42:1 to ∞	22	341:1	75:1 to ∞	46
Scarified unshaded	74:1	10:1 to ∞	1	1,875:1	188:1 to ∞	4	∞		0
Unscarified shaded	19:1	4:1 to 375:1	5	144:1	14:1 to ∞	13	312:1	54:1 to ∞	46
Unscarified unshaded	46:1	9:1 to ∞	2	750:1	94:1 to ∞	6	∞		0

[1]*Ratio of germinating seedlings to survival at the end of the first growing season.*
[2]*Ratio of seedlings alive at the end of the first growing season to seedlings alive at the end of 5 growing seasons.*
[3]∞ = *no germination or survival.*

DISCUSSION

The important factors influencing natural regeneration of Engelmann spruce after clearcutting in the central Rocky Mountains based on this study and literature reviewed by Noble (1974), are summarized in figure 10.

Natural regeneration of spruce requires sufficient viable seeds falling in microenvironments favorable for germination and survival. Variability in seed viability and dispersal was reduced in this study by artificially sowing a known number of viable seeds, allowing research efforts to concentrate on factors affecting germination and initial survival. Although the techniques used could not adequately measure the microenvironments of individual seedlings, it was possible to characterize the microenvironment of seedbeds which influenced how seedlings responded. Those factors having a major effect on the seedbed include (1) weather, (2) aspect, and (3) cultural treatments. Biotic factors (primarily clipping of seed coats by birds) did not directly affect seedbeds, but did affect regeneration success.

Weather

Threshold temperature and precipitation values in figure 10 are reasonable guides. However, the distribution of precipitation during the growing season and the time and duration of temperature extremes are also important factors that influence the threshold values.

Generally, temperature and precipitation work together, but not always. A single rainstorm of high intensity can wash away both seeds and seedlings, while unusually low midsummer temperatures can cause frosts which damage current growth of established seedlings and kill newly emerged seedlings. Both conditions occurred during the period of observation, but were relatively infrequent. Their potential for serious losses to regeneration in spruce-fir forests should not be overlooked, however (Roe et al. 1970).

The interactions of temperature and precipitation that resulted in seedling mortality from drought and frost heaving were more serious. Drought—excessive loss of moisture from soil and seedlings—generally resulting from low and/or irregular precipitation and high air temperatures for several weeks, may occur at any time during the growing season. It is most limiting to spruce regeneration and seedling survival during the period immediately following spring snowmelt. At elevations where spruce grows, high air temperatures may not contribute as much to drought induced low germination and poor seedling survival as does low and/or irregular precipitation. For example, 1971 was a poor year for germination on both aspects (0.9%), and precipitation was below average and poorly distributed. During the 6 weeks following snowmelt, the north aspect received 3.8 cm of precipitation in 8 storms, compared to the average of 8.9 cm of precipitation in 11 storms; the south aspect received 4.8 cm of precipitation in storms, compared to an average of 9.6 cm in 9 storms. Mean maximum air temperatures were about 1.5° C above average on the north aspect and about average on the south aspect. In contrast, 1972 was a good year for germination on the south aspect (14%) and an average

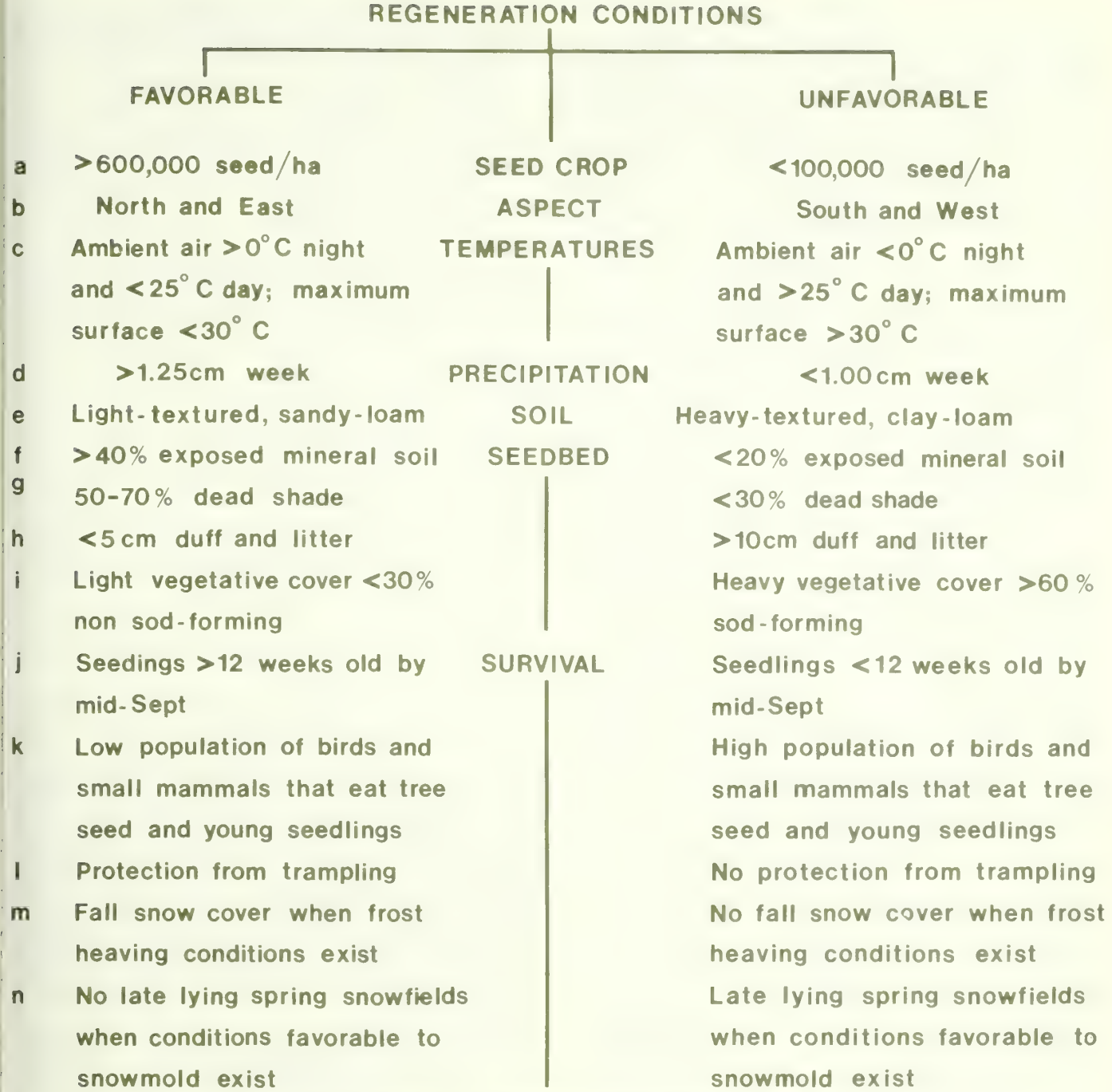

Figure 10.—Conditions favorable and unfavorable to natural regeneration of Engelmann spruce.

year on the north aspect (6%). The south aspect received 9.3 cm of precipitation in 14 storms; on the north aspect 7.6 cm of precipitation fell in 9 storms. Mean maximum air temperatures were about average on the north aspect and about 0.5° C above average on the south aspect, for the first 6 weeks after spring snowmelt.

Frost heaving—resulting from the interaction of moisture and temperature—was a serious cause of mortality, especially on the north aspect. Frost heaving occurred when soil moisture was at or near field capacity, there was no vegetational or snow cover, and day-night temperatures were alternating above and below 0° C. Seedling losses from frost heaving were recorded every year on the north aspect, but were more severe in some years than others. Frost heaving is most likely to occur during the first 2 to 3 weeks following snowmelt in the spring, and again in the fall just before permanent snow cover.

The effects of other weather factors—radiation, vapor pressure defects (VPD's), and wind—become more apparent when considered with aspect.

Aspect

This study was specifically planned to describe the environment in relation to spruce regeneration on a north and a south aspect. The study areas were only about 7.2 km apart, in the same major drainage, and at the same elevation and slope. Because of local topography, the south aspect averages slightly more precipitation (3.0 cm) during the growing season. However, the distribution patterns were very similar, and no substantial differences in wind patterns were evident, indicating that the same major air mass generally covered both aspects. The effects of net radiation, VPD, and temperature on regeneration success, therefore, were more apparent when related to aspect.

Maximum surface temperatures on all four seedbed treatments averaged from 2.2° C to 11.0° C higher on the south aspect, even though air temperatures measured at 1.37 cm above the ground either in the open or in the weather shelters averaged less than 1° C warmer on the south aspect. The higher surface temperatures on the south aspect caused greater soil temperatures at 2.5, 5.1, 10.2, and 20.3 cm below the surface. However, air temperatures at 2.5, 5.1, 10.2, and 20.3 cm above the surface were generally 1–2° C higher on the north aspect.

This anomaly of higher air profile temperatures above the surface on the north aspect occurred because the north aspect was in direct sunlight from shortly after sunrise to sunset, whereas the south aspect was shaded by late afternoon as the sun moved behind the high ridge just to the west and above the study area. The higher surface and soil temperatures, plus VPD's averaging about 8% higher on the south aspect, increased evapotranspiration rates and created a drier environment. The result was poorer germination and higher seedling mortality from drought and heat girdle—the death of stem tissue near the ground surface in newly emerged seedlings resulting from the interaction of high surface temperatures and dry soils.

Snowmelt was usually 7 to 10 days earlier on the south aspect. Early snowmelt followed by periods of low and/or irregular precipitation during the first critical weeks limited spruce regeneration success. Seedbeds changed rapidly from too cold and wet for germination to too hot and dry for most seedlings to emerge. Those seedlings that did emerge could not survive the hot, dry weather. These later circumstances were largely responsible for the lack of any survival on the south aspect for seeds sown after 1973.

The greater net radiation of at least 8% on the south aspect was largely responsible for the higher seedbed surface temperatures and vapor pressure defects. However, high light intensity (solar radiation) was not directly limiting to regeneration success. Few seedlings died from insolation (solarization) on either aspect.

Seedbed Treatments

On the north aspect, scarification improved the microenvironment of the seedbeds for germination and survival, probably by increasing available soil moisture. Shade also improved the seedbed microenvironment for survival by reducing temperatures, but only in those years when snowmelt was followed by periods of regular summer precipitation. On the south aspect, shade and the combination of shade and scarification improved the seedbed microenvironment for both germination and survival. Eis (1970), working in spruce-fir forests in the interior of British Columbia, found that available soil moisture at a depth of 5 cm was substantially higher in mineral soil than in humus. Day (1963), working in Alberta, reported that shade reduced water losses from both seedlings and soil. Results of this study generally agree with this earlier work. The layer of organic matter on the north aspect was 7 cm or more thick, and scarification most likely increased available soil moisture. In contrast, the organic layer on the south aspect was less than 5 cm thick, and scarification was less effective. However, because of high surface temperatures, it is likely that scarification would be less effective on south aspects, regardless of the thickness of the organic layer. The fact that shade was essential to any regeneration success on the south aspect and improved survival on the north aspect reemphasizes the importance of reducing water losses from soil and seedlings in clearcut openings in spruce-fir forests.

Biotic Factors

The significant biotic factors affecting regeneration were clipping of cotyledons on newly germinated seedlings, and snowmold. Initially rodents were suspected of doing the clipping; but by periodic trapping inside the exclosures, and from visual and photographic evidence, it was determined that grey-headed juncos (*Junco caniceps* Woodhouse) were responsible (Noble and Shepperd 1973). Snowmold fungus (*Herpotrichia nigra* Hartig) was largely confined to the north slope. It caused more damage than mortality, but it occurred every year on those plots that were shaded and in depressions where snow normally accumulated and melted slowly. Snowmold also occurred on other plots in those years when snowfall was heavy or when weather retarded spring snowmelt.

Other biotic factors causing seed and seedling losses such as damping-off fungi, insects, and needlecast were not limiting to regeneration success.

Seed:Seedling Ratios

A reasonable stocking goal for Engelmann spruce is 1,976 seedlings per hectare at age 5 years (Alexander and Edminster 1980). This is more than required for adequate stocking, but necessary to achieve uniform spacing, allow for possible future mortality, and provide options in selecting crop trees in subsequent thinnings. Numbers of seeds, based on seed to 5-year seedling ratios in table 5, required to produce this stocking level under different seedbed conditions on north and south aspects are shown in table 6.

Table 6.—Number of viable seeds per ha required to produce 1,976 five-year-old Engelmann spruce seedlings in relation to seedbed treatments and aspect[1] (Alexander 1983)

Seedbed treatment	North Aspect	South Aspect
Scarified-shaded	63,232	673,816
Scarified-unshaded	150,176	[2]∞
Unscarified-shaded	142,272	616,512
Unscarified-unshaded	823,992	∞

[1]*Data presented are based upon the exclusion of seed-eating mammals. If these animals are not excluded, numbers of seed required should be increased by 50% to 100%.*
[2]*∞ = no survival.*

Data presented in tables 5 and 6 are minimums, based upon the exclusion of seed-eating small mammals, but not birds that consume tree seeds. All spruce-fir forests support populations of these small mammals; and any disturbance that initiates understory plant succession probably favors a buildup of these populations, particularly if slash and other downed materials are present to provide cover. Although these mammals consume considerable amounts of seed, the magnitude of the loss is not known in the central Rocky Mountains. However, losses to seed-eaters are more important in years of poor seed production, or years when populations of seed-eating mammals are high.

CONCLUSIONS

Clearcut openings 1 to 2 ha on north aspects, in spruce-fir forests, in the central Rocky Mountains can be successfully regenerated naturally from seed with the aid of cultural treatments. Based on a stocking goal of 1,976 5-year-old seedlings per hectare, and previously published data on seed production (Alexander et al. 1982) and seed dispersal (Alexander and Edminster 1983) scarified-shaded seedbeds should restock within a 5-year period, but may require more than one good seed year.[3] It will require a number of good seed years to restock scarified-unshaded and unscarified-shaded seedbeds, and it is not likely to be accomplished within a 5-year period. Unscarified-unshaded seedbeds in small clearcut openings on north aspects are not likely to restock adequately within a 20-year period. On south aspects, small clearcut openings are not likely to restock adequately, regardless of cultural treatments, in a reasonable amount of time. They will have to be regenerated with different cutting methods that either take advantage of advanced reproduction or provide overstory protection for new natural or planted reproduction.

Weather variables (i.e., ambient air temperature, precipitation, wind, vapor pressure deficit) and net radiation are interrelated and important for describing microclimate conditions. Microclimatic conditions near the surface of small forest openings, on comparable high-elevation north and south aspects in the Colorado Rockies are quite different, however; and standard weather measurements of air temperature, precipitation, and wind do not adequately indicate those differences. Better indicators are vapor pressure deficits and net incident radiation. Additional factors affected by microclimate and aspect in forest openings at high elevations that should be better quantified include evapotranspiration rates and soil-plant-water relationships.

[3]*A good seed year produces 247,000 to 617,500 sound seeds per hectare under uncut stands surrounding the cleared opening.*

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Table A-1.—Mean hourly maximum, minimum and mean air temperatures (°C) by aspect during the growing season for the years 1969-1982

Year	June[1]			July			August			September			October[2]			Seasonal		
	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean
North Aspect																		
1969	11.4	0.2	4.7	19.5	6.7	11.8	19.2	6.4	12.1	12.7	1.1	5.6	1.6	-8.3	-4.2	12.9	1.2	5.9
1970	18.5	5.6	12.0	18.4	5.3	11.5	17.6	5.5	10.8	10.8	-1.6	4.1	5.3	-4.5	-0.1	14.1	2.1	7.7
1971	19.1	6.2	13.0	18.6	5.4	12.1	17.4	4.0	10.1	10.8	-1.7	4.4	7.3	-3.9	1.5	14.7	2.0	8.2
1972	15.9	2.7	9.1	18.9	4.8	11.9	16.8	3.9	9.8	11.6	1.1	6.1	—	—	—	15.8	3.1	9.2
1973	15.4	2.4	9.1	15.9	3.6	9.5	16.7	4.2	9.9	10.6	-1.1	4.4	—	—	—	14.7	2.3	8.2
1974	15.6	3.1	9.7	16.8	4.3	10.2	16.5	3.4	9.8	12.1	-0.4	5.6	7.0	-2.8	1.4	13.6	1.6	7.3
1975	14.7	-1.2	7.1	18.1	4.2	10.7	16.9	3.3	10.0	12.3	0.1	5.7	7.7	-5.4	0.9	13.9	0.2	6.9
1976	13.6	0.5	7.2	19.1	5.1	11.9	15.7	3.1	9.1	11.4	0.2	5.4	—	—	—	14.9	2.2	8.4
1977	18.6	4.6	11.7	17.7	5.8	12.0	16.9	5.1	10.5	13.7	1.2	6.9	5.9	-4.7	0.5	14.6	2.4	8.3
1978	18.2	5.9	12.2	20.2	5.2	12.8	16.8	2.7	9.4	13.1	-0.2	6.2	9.4	-2.1	3.2	15.5	2.3	8.8
1979	17.1	3.1	10.6	19.1	4.4	11.6	16.4	4.0	9.7	15.7	2.3	8.4	7.9	-3.6	2.1	15.2	2.1	8.4
1980	—	—	—	19.5	5.2	12.2	16.8	3.4	9.8	13.7	0.7	6.9	7.7	-3.5	1.7	14.4	1.5	7.7
1981	18.7	4.3	11.6	17.9	4.9	11.1	16.3	2.8	9.1	13.4	0.9	6.6	6.9	-1.4	2.1	14.5	2.3	8.1
1982	—	—	—	17.3	3.9	10.4	16.9	4.3	10.1	10.6	0.1	4.9	—	—	—	14.9	2.8	8.4
Aver.	16.4	3.1	9.8	18.3	4.9	11.4	16.9	4.0	10.0	12.3	0.2	5.8	6.7	-4.0	0.9	14.1	1.6	7.6
South Aspect																		
1969	11.5	1.6	5.2	20.0	7.7	13.2	20.5	7.7	13.0	14.4	2.7	7.5	2.1	-7.4	-2.9	13.7	2.4	7.2
1970	18.2	7.1	12.2	19.2	6.4	11.9	18.9	7.2	12.0	12.0	-0.1	5.5	6.2	-3.1	0.4	14.9	3.5	8.4
1971	19.8	6.7	12.5	18.4	6.2	11.5	18.2	5.6	10.8	11.0	-1.6	4.3	8.4	-3.2	2.0	15.2	2.8	8.2
1972	16.0	3.8	9.6	19.6	6.3	12.4	17.6	5.6	10.7	12.1	2.1	6.6	—	—	—	16.3	4.4	9.8
1973	15.7	3.8	9.6	17.7	5.6	11.0	18.3	6.7	11.8	12.6	1.4	6.7	—	—	—	16.1	4.4	9.8
1974	16.6	4.4	10.1	17.6	5.9	10.8	17.3	5.2	10.6	13.2	1.1	6.5	7.8	-1.2	2.2	14.5	3.1	8.1
1975	16.7	2.3	9.7	19.2	6.6	12.1	17.7	5.3	11.1	13.2	1.8	6.9	8.7	-3.5	2.3	15.1	2.5	8.4
1976	12.4	0.7	6.8	18.5	6.3	11.9	15.6	4.1	9.3	11.1	1.2	5.6	—	—	—	14.4	3.1	8.4
1977	17.9	5.2	11.2	17.7	6.1	11.4	15.9	5.3	10.1	12.9	1.8	6.7	5.1	-4.6	0.2	13.9	2.7	7.9
1978	18.9	7.7	13.4	21.5	8.3	14.6	17.6	5.1	10.8	13.5	1.6	7.1	10.4	-1.1	3.8	16.4	4.4	10.0
1979	19.5	6.1	12.8	20.1	6.9	12.8	17.3	6.4	11.0	17.3	4.6	10.2	10.2	-0.7	4.3	16.9	4.7	10.2
1980	—	—	—	20.9	8.2	14.1	17.7	5.6	11.0	14.9	2.9	8.4	8.7	-1.8	2.7	15.6	3.7	9.1
1981	16.6	3.4	9.8	16.8	4.9	10.3	17.1	5.0	10.3	14.7	3.0	7.9	7.4	0.0	3.2	14.6	3.3	8.3
1982	—	—	—	18.1	6.3	11.7	17.6	6.8	11.2	11.6	2.2	6.4	—	—	—	15.8	5.1	9.8
Aver.	17.8	4.4	10.2	18.9	6.6	12.1	17.7	5.8	11.0	13.2	1.8	6.9	7.5	-2.7	1.8	14.8	3.2	8.4

[1]*June averages are based upon measurements taken during part of the month following activation of weather station which varied from June 3 to June 30, depending upon the time of snowmelt.*

[2]*October averages are based upon measurements taken during part of the month preceding deactivation of weather station which varied from October 1 to October 30, depending upon time of snowfall.*

Table A-2.—Mean monthly precipitation (cm) during the growing season by aspect for the years 1969-1982

Year	Total months record	June	July	Aug.	Sept.	Oct.	Seasonal Total	Seasonal Aver.
				North Aspect				
1969	4	13.26	3.76	5.74	5.92	-	28.68	7.17
1970	5	0.90	4.60	7.24	9.50	0	22.24	4.45
1971	5	0.68	3.12	4.42	5.26	4.12	17.60	3.52
1972	4	5.18	2.41	7.82	6.96	-	22.37	5.59
1973	4	2.79	10.72	4.01	4.68	-	22.20	5.55
1974	5	8.46	8.86	2.26	3.25	4.19	27.02	5.40
1975	5	0.61	5.05	5.69	3.58	5.05	19.98	4.00
1976	4	4.44	6.25	6.63	8.71	-	26.03	6.51
1977	5	2.97	11.00	6.27	4.44	5.33	30.01	6.00
1978	4	0	2.36	2.34	1.73	-	6.43	1.61
1979	5	0.53	4.62	6.48	1.19	2.01	14.83	2.97
1980	4	0	3.99	4.90	3.91	0.08	12.88	3.22
1981	5	1.12	8.20	5.84	3.91	1.04	20.11	4.02
1982	3	0	1.83	6.55	5.38	-	13.77	4.60
Total	62	40.94	76.77	76.19	68.42	21.82	284.18	
Aver.	4.43	3.40	5.48	5.44	4.89	2.73	21.94	4.58
				South Aspect				
1969	4	14.53	5.16	5.61	9.12	-	34.42	8.60
1970	5	0.43	2.92	8.99	9.02	0.05	21.41	4.28
1971	5	0.68	4.12	7.21	7.32	3.23	22.56	4.51
1972	4	6.45	2.87	7.85	8.72	-	25.89	6.47
1973	4	4.01	9.35	3.30	6.83	-	23.49	5.87
1974	5	11.25	8.41	2.36	4.14	4.80	30.96	6.19
1975	5	0.25	5.79	4.25	2.46	6.45	19.20	3.84
1976	4	5.13	4.27	6.35	9.68	-	25.43	6.35
1977	5	1.98	8.61	7.47	4.88	6.09	29.03	5.81
1978	4	0.36	2.79	3.02	2.44	-	8.61	2.15
1979	5	0.94	4.19	9.58	1.30	2.87	18.88	3.78
1980	4	-	8.15	5.77	6.20	0.36	20.48	5.12
1981	5	2.79	7.24	4.19	6.27	1.47	21.96	4.39
1982	3	-	3.25	10.64	6.66	-	20.55	6.86
Total	62	48.80	77.12	86.59	85.04	25.32	322.87	
Aver.	4.43	4.07	5.51	6.18	6.07	3.16	24.99	5.21

Table A-3.—Average daily maximum, minimum and mean vapor pressure deficits (mm Hg) by aspect during the growing season for the years 1968-1982

Year	June			July			August			September			October			Seasonal		
	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean
North Aspect																		
1969	12.43	2.69	9.26	14.75	8.02	12.00	16.42	3.84	10.44	10.52	5.25	7.46	5.35	2.51	4.03	11.89	4.46	8.64
1970	14.19	9.13	11.66	13.14	2.78	10.48	13.97	3.45	8.15	7.66	2.30	5.23	5.71	2.43	3.53	10.93	4.02	7.81
1971	13.14	6.89	10.42	10.87	5.88	8.74	12.62	5.56	9.53	8.85	1.81	6.51	8.68	2.15	6.12	10.83	4.46	8.26
1972	9.00	7.65	8.15	11.27	9.31	10.16	12.10	6.09	9.02	8.51	0.95	5.31	-	-	-	10.22	6.00	8.16
1973	10.76	3.37	7.83	11.64	0.76	6.78	10.50	6.32	8.20	10.43	0.97	7.12	-	-	-	10.83	2.86	7.48
1974	16.12	3.82	12.35	13.32	5.67	10.13	11.09	9.01	10.42	12.08	4.71	8.50	8.13	2.68	5.26	12.15	5.18	9.33
1975	13.59	5.98	8.83	15.73	9.48	12.03	15.77	5.18	9.52	13.67	5.24	8.47	8.80	1.83	6.35	13.51	5.54	9.04
1976	15.60	1.71	9.73	14.55	8.24	10.80	13.43	6.78	10.27	9.97	0.68	5.95	-	-	-	13.88	4.35	9.19
1977	16.33	10.90	13.28	14.76	2.98	10.74	15.47	5.89	11.10	12.27	6.63	9.39	4.13	1.32	2.55	12.59	5.54	9.41
1978	14.07	10.47	11.91	17.63	11.60	14.08	12.62	7.11	10.40	12.99	6.17	9.26	8.57	5.85	6.82	13.18	8.24	10.49
1979	14.64	1.38	9.46	15.47	9.00	12.32	15.69	0.88	9.22	15.02	6.83	9.88	9.80	0.88	6.11	14.12	3.79	9.40
1980	-	-	-	16.00	7.29	11.69	14.96	5.71	11.28	9.46	7.02	8.35	9.80	2.07	6.56	12.56	5.52	9.47
1981	11.75	5.24	9.07	15.77	7.93	12.31	12.80	5.67	9.21	10.33	4.16	7.67	-	-	-	12.66	5.75	9.56
1982	-	-	-	14.27	4.69	10.56	14.08	8.24	10.18	8.85	5.80	7.32	9.54	2.58	6.04	11.68	5.33	8.52
Aver.	13.47	5.77	10.16	14.27	6.69	10.92	13.68	5.70	9.78	10.76	4.18	7.60	7.75	2.43	5.34	11.97	4.95	8.76
South Aspect																		
1969	12.52	2.85	9.52	16.55	11.26	13.43	18.06	6.76	13.12	13.32	6.93	9.57	7.36	2.94	5.14	13.56	6.15	10.16
1970	14.47	11.45	12.96	14.76	4.32	11.78	15.27	3.84	9.43	7.96	3.14	6.47	8.38	3.07	4.87	12.17	5.17	9.10
1971	14.18	10.02	12.02	14.34	5.50	10.18	12.70	5.97	10.60	11.69	2.52	8.42	10.47	2.66	7.55	12.68	5.33	9.75
1972	9.80	8.25	8.88	13.26	10.47	11.68	14.08	8.54	10.80	10.61	0.73	5.85	-	-	-	11.94	7.00	9.30
1973	10.87	2.39	7.74	14.37	1.91	8.89	10.87	7.29	8.71	11.60	0.82	7.74	-	-	-	11.93	3.10	8.27
1974	15.93	3.67	12.09	13.43	5.43	9.56	15.07	8.48	11.00	12.43	4.27	8.05	8.43	3.02	5.23	13.06	4.97	9.19
1975	14.88	5.12	8.56	19.15	11.26	13.23	14.07	6.17	9.57	15.67	4.05	9.01	9.46	1.50	6.71	14.65	5.62	9.42
1976	14.57	1.08	9.71	13.25	9.67	11.37	13.27	4.32	10.76	11.26	0.97	8.01	-	-	-	13.09	4.01	9.96
1977	15.42	10.33	12.25	13.79	2.99	9.91	14.02	5.02	10.47	12.70	5.92	8.99	1.68	0.90	1.12	11.52	5.03	8.55
1978	13.60	10.52	11.99	19.30	11.18	15.10	13.43	7.14	11.39	14.27	5.54	10.92	9.84	6.44	7.91	14.09	8.16	11.46
1979	14.96	13.33	13.55	15.67	9.82	13.14	14.62	0.17	8.73	15.73	7.51	10.77	11.49	0.33	7.00	14.49	6.23	10.64
1980	-	-	-	16.08	5.69	12.70	15.26	6.59	11.63	12.01	7.97	9.79	12.17	5.30	8.70	13.88	6.39	10.70
1981	12.11	4.20	8.73	16.33	7.42	12.12	13.67	6.57	10.74	11.39	4.27	8.41	-	-	-	13.38	5.62	10.00
1982	-	-	-	14.55	4.02	10.50	15.02	9.10	11.26	10.60	6.34	8.47	10.43	2.98	6.62	12.65	5.61	9.21
Aver.	13.61	6.93	10.67	15.34	7.21	11.68	14.24	6.00	10.59	12.23	4.36	8.60	8.97	2.91	6.08	12.88	5.48	9.52

Table A-4.—Average daily maximum, minimum and mean incident radiation (ly) by aspect during the growing season for the years 1969-1982

Year	June			July			August			September			October			Seasonal		
	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean
North Aspect																		
1969	589	493	533	695	571	632	593	428	506	506	353	407	264	218	247	529	413	465
1970	699	531	636	690	472	579	540	381	448	471	344	413	432	206	305	566	387	476
1971	781	370	593	708	589	644	622	369	496	533	402	468	404	301	340	610	406	508
1972	759	588	639	710	564	657	578	385	468	432	363	402	388	191	274	573	418	488
1973	677	549	622	705	377	552	550	402	474	454	331	405	326	259	286	542	384	468
1974	693	510	622	696	477	547	584	495	537	510	428	470	442	127	297	585	407	495
1975	701	538	627	624	553	587	610	440	522	540	329	441	444	233	346	584	419	505
1976	696	580	631	601	442	539	543	413	496	503	253	364	370	296	337	543	397	473
1977	704	518	590	701	397	555	518	382	450	474	385	430	385	250	317	556	386	468
1978	761	504	658	648	579	606	609	511	538	482	353	413	421	216	334	584	433	510
1979	636	572	613	618	513	547	496	389	420	473	388	438	421	240	333	529	420	470
1980	768	680	717	654	489	583	544	382	491	479	432	456	441	193	338	577	435	517
1981	703	606	657	533	472	503	523	339	444	432	368	397	308	228	282	500	403	456
1982	660	487	564	596	482	546	454	348	390	339	285	308	348	264	303	479	373	422
Aver.	702	538	622	656	498	577	555	405	477	473	358	415	385	230	310	554	406	480
South Aspect																		
1969	585	488	528	690	582	638	622	469	546	579	425	485	382	303	337	572	453	507
1970	691	526	630	685	472	585	577	416	484	569	429	492	557	275	414	616	424	521
1971	773	368	587	731	600	651	643	411	531	626	486	557	541	434	464	663	460	558
1972	751	584	633	734	575	665	607	429	504	538	413	480	500	276	370	626	455	530
1973	670	546	616	700	381	557	588	488	511	519	412	482	453	334	392	586	432	512
1974	686	507	616	689	487	551	625	522	572	594	517	560	554	183	393	630	443	538
1975	694	533	621	624	571	593	645	471	564	622	386	526	573	337	468	632	460	554
1976	689	570	623	597	457	544	593	450	536	574	316	431	513	435	472	593	446	521
1977	696	513	585	724	405	571	544	417	486	542	452	514	535	344	432	608	426	518
1978	753	501	651	660	583	612	639	546	580	551	427	492	543	317	454	629	475	558
1979	630	568	607	617	510	552	520	416	453	567	484	522	421	240	450	551	444	517
1980	764	692	710	666	489	590	571	426	530	598	522	560	569	269	457	634	480	569
1981	695	602	650	544	469	509	559	370	490	523	432	474	445	317	385	553	438	502
1982	656	482	559	595	492	549	476	388	419	410	335	373	450	382	409	517	416	462
Aver.	695	534	615	661	505	583	586	444	515	558	431	496	503	318	421	600	446	526

Table A-5.—Mean daily and peak gust wind velocity (km/hr) by aspect during the growing season for the years 1970-1982

Year	June		July		August		September		October		Total		Average	
	HR	PG	HR	PG	HR	PG	HR	PG	HR	PG	HR	PG	HR	PG
North Aspect														
1970	-	-	-	-	2.2	5.5	3.1	8.4	2.1	5.5	7.4	19.4	2.5	6.4
1971	-	-	3.9	9.5	3.5	7.7	3.7	10.1	3.4	9.2	14.5	36.5	3.6	9.1
1972	4.2	11.1	3.5	8.8	2.7	6.8	2.9	8.4	-	-	13.3	35.1	3.3	8.8
1973	3.5	9.2	3.4	7.4	2.9	6.6	2.9	7.6	-	-	12.7	30.8	3.2	7.7
1974	3.5	9.8	2.6	7.2	2.7	8.8	2.6	8.2	2.9	8.5	14.3	42.5	2.9	8.5
1975	4.4	10.9	2.6	6.9	2.2	7.1	1.9	6.8	2.7	7.9	13.8	39.6	2.8	7.9
1976	4.2	11.8	2.7	7.4	2.4	6.8	1.8	5.2	-	-	11.1	31.2	2.8	7.8
1977	3.4	8.7	2.6	6.8	2.4	6.6	2.9	7.7	-	-	11.3	29.8	2.8	7.4
1978	3.9	10.1	2.1	7.2	2.1	7.1	1.9	6.8	2.2	7.9	12.2	39.1	2.4	7.8
1979	2.7	9.7	1.8	6.6	1.6	6.4	1.6	6.3	1.9	8.0	9.6	37.0	1.9	7.4
1980	-	-	2.6	6.8	2.2	6.8	3.1	6.8	1.9	5.0	9.8	25.4	2.4	6.4
1981	2.2	6.1	0.8	2.9	0.8	2.1	0.6	1.9	0.5	2.1	4.9	15.1	1.0	3.0
1982	-	-	1.6	3.9	1.0	2.6	1.5	3.1	1.3	4.5	5.4	14.1	1.4	3.5
Total	32.0	87.4	30.2	81.4	28.7	80.9	30.5	87.3	18.9	58.6	140.3	395.6		
Aver.	3.6	9.7	2.5	6.8	2.2	6.2	2.4	6.7	2.1	6.5	12.8	35.9	2.6	7.2
South Aspect														
1970	-	-	-	-	1.8	5.8	4.2	11.2	4.0	10.0	10.0	27.0	3.3	9.0
1971	-	-	3.5	10.1	1.9	6.8	4.2	13.2	4.2	13.8	13.8	43.9	3.4	11.0
1972	3.7	15.6	3.5	11.4	2.9	8.5	4.3	14.6	-	-	14.4	50.1	3.6	12.5
1973	5.3	15.1	3.5	10.1	3.5	10.3	4.5	11.6	-	-	16.8	47.1	4.2	11.8
1974	4.4	12.4	2.9	9.0	3.7	12.1	3.7	12.1	3.7	11.4	18.4	57.0	3.7	11.4
1975	5.3	16.7	2.6	8.7	2.7	10.5	2.6	9.8	3.4	11.4	16.6	57.1	3.3	11.4
1976	5.5	17.4	2.9	9.0	2.9	9.3	2.6	8.2	-	-	13.9	43.9	3.5	11.0
1977	3.7	12.4	2.4	9.2	3.2	11.6	4.3	14.5	-	-	13.6	47.7	3.4	11.9
1978	3.9	13.7	3.1	11.6	3.1	11.2	2.9	10.8	4.2	13.8	17.2	61.1	3.4	12.2
1979	2.7	11.9	2.4	9.7	1.9	9.3	2.4	9.2	3.5	12.7	12.9	52.8	2.6	10.6
1980	-	-	3.9	11.1	4.0	11.6	4.5	13.2	4.2	10.0	16.6	45.9	4.2	11.5
1981	3.5	9.3	1.4	4.3	1.3	3.7	1.4	4.5	1.6	4.5	9.2	26.3	1.8	5.3
1982	-	-	3.7	7.1	1.1	3.4	1.3	4.2	2.6	8.2	8.7	22.9	2.2	5.8
Total	38.0	124.5	35.8	111.3	34.0	114.1	42.9	137.1	31.4	95.8	182.1	582.8		
Aver.	4.2	13.8	3.0	9.3	2.6	8.8	3.3	10.5	3.5	10.6	16.6	53.0	3.3	10.6

Alexander, Robert R. 1984. Natural regeneration of Engelmann spruce after clearcutting in the central Rocky Mountains in relation to environmental factors. USDA Forest Service Research Paper RM-254, 17 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Successful natural regeneration of Engelmann spruce in small clearcut openings depends on weather and aspect and is modified by cultural treatments. Small clearcut openings (1–2 ha) can be successfully regenerated on north aspects with mineral soil seedbeds and shade. On south aspects, shade is absolutely essential for any survival. However, successful natural regeneration is not likely regardless of cultural treatments. Drought is the most serious cause of mortality; but clipping by birds, frost heaving (north aspect), heat girdle (south aspect), and snowmold (north aspect) caused significant losses.

Keywords: *Picea engelmannii*, Engelmann spruce, natural regeneration, environmental factors

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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United States
Department of
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Forest Service

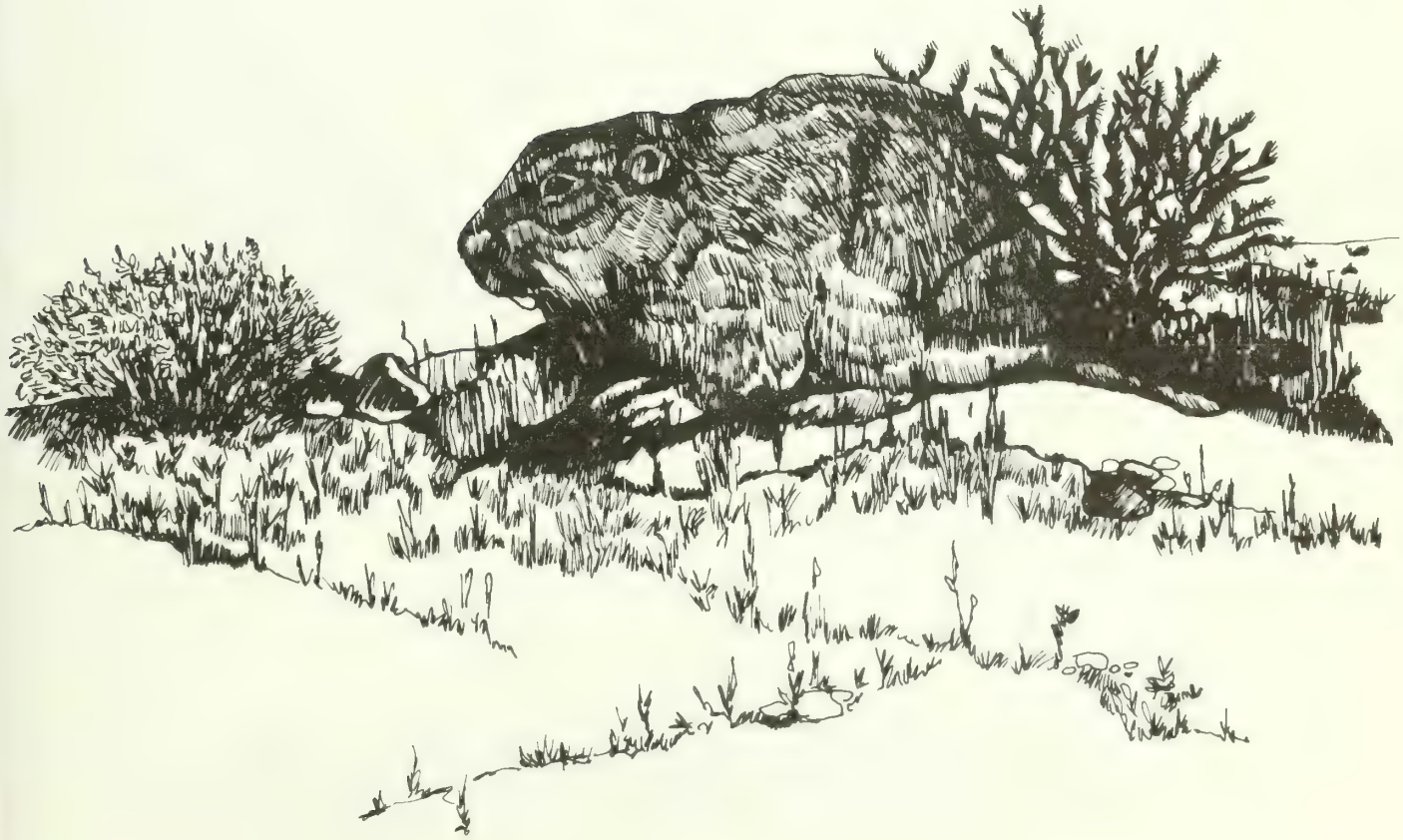
**Rocky Mountain
Forest and Range
Experiment Station**

Fort Collins,
Colorado 80526

**Research Paper
RM-255**

Pocket Gopher Food Habits on Two Disturbed Forest Sites in Central Arizona

Gerald J. Gottfried and David R. Patton



Abstract

Stomach analysis of pocket gophers *(Thomomys bottae)* indicated that on one area succulent grasses were the main food item, supplying between 84% and 44% of the average composite diet. Bromegrasses *(Bromus* spp.) were highly preferred. Thistle *(Cirsium* spp.) was the main forb eaten. The second area supported a forb-grass-brush cover after the forest had been removed. Forbs comprised about 70% of the herbaceous cover, and supplied 51% of the diet; grasses and sedges *(Carex* spp.) averaged 25% of the diet. Fleabane *(Erigeron* spp.) and common sunflower *(Helianthus annuus)* were the main forbs in the diet. Woody material, including ponderosa pine *(Pinus ponderosa)*, was not used heavily throughout the period, although use did increase slightly during the winter. Insects were between 8% and 19% of the average diet.

JDA Forest Service
Research Paper RM-255

August 1984

Pocket Gopher Food Habits on Two Disturbed Forest Sites in Central Arizona

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Pocket Gopher Food Habits on Two Disturbed Forest Sites in Central Arizona

Gerald J. Gottfried and David R. Patton

MANAGEMENT IMPLICATIONS

It often is difficult to regenerate conifers once the atural or seeded herbaceous and brush cover is estab- shed. Herbaceous cover competes with conifer seed- ngs for moisture (Embry 1971) and light, and supports a dent population which feeds on the young trees. egeneration activities should be started as soon as ossible after a wildfire or harvesting activity to reduce ese problems.

Although grass seeding provides rapid revegetation, it so improves gopher habitat. Therefore, grass should e seeded only where erosion is a problem and where nge and wildlife benefits are the prime consideration. is difficult and expensive to reduce natural or seeded egetation and the associated pocket gopher *(Thomomys ottae)* populations once they occupy a site; but vegeta- on control may reduce both problems.

Researchers in Colorado (Keith et al. 1959, Tietjen et . 1967) have suggested that gophers can be controlled y eliminating the forb component of the vegetation on igh elevation grasslands. Results from this study as ell as those of Burton and Black (1978), indicate that rasses also must be eliminated in some areas. Gopher opulations should decline naturally after their food is estroyed. Follow-up herbicide operations may be ecessary to maintain poor gopher habitat, or direct ontrol measures could be used on the remaining nimals.

Reforestation should be delayed until gopher popula- ons have been sufficiently reduced to insure seedling uccess (Burton and Black 1978). Gopher control before arvest and rapid regeneration are recommended on reas with potential problems (Crouch 1982). A knowl- dge of gopher food habits as well as of their habitat re- uirements can help foresters identify lands where eforestation could be a problem. It gives managers the ption of controlling gophers by direct methods or by anipulating their food sources.

INTRODUCTION

Pocket gophers, especially of the genus *Thomomys*, inder successful forest regeneration on disturbed sites roughout the western United States (Crouch 1982, urton and Black 1978, Heidmann 1972). Gophers kill onifer seedlings by cutting the roots or tops, or by girdling the roots or boles of larger seedlings and small saplings.

Pocket gophers are not common in a dense forest environment but are usually confined to natural meadows where there is sufficient food. The increase in herbaceous vegetation after overstory removal provides gophers with an adequate food supply.

Food habit studies have been conducted on *Thomomys talpoides* in Colorado (Keith et al. 1959, Ward 1960, Ward and Keith 1962) and in Utah (Marston and Julander 1961), and on *T. mazama* in Oregon (Burton and Black 1978). The Colorado research indicated that gopher populations can be reduced by controlling the forb cover. Keith et al. (1959) found an 87% reduction in gopher numbers, on a mountain grassland, after a herbicide treatment which reduced the perennial forb cover by 83%. Tietjen et al. (1967) concluded that *T. talpoides* cannot survive where succulent forbs have been eliminated, and that grass will only provide a marginal diet. However, they indicated that succulent grasses or those with corms or rhizomes will supply a subsistance diet.

The valley pocket gopher occurs throughout Arizona and parts of California. It has received relatively little study, although the various subspecies can be found from the desert shrub into the high elevation mixed conifer forests. *Thomomys bottae* food habits have only been studied by Bandoli (1981) in a pinyon-juniper shortgrass prairie, northeast of Flagstaff, and to some extent by Goodwin and Hungerford (1979) who were studying rodent populations within a managed ponderosa pine *(Pinus ponderosa)* forest south of Flagstaff.

Objectives of this study were to determine gopher food habits on two non-stocked forest sites where repeated attempts to plant ponderosa pine seedlings have had limited success, partially because of gophers. The study included the identification of preferred forb and grass species, and the relative extent that pine was utilized.

STUDY AREA

The study was conducted on two sites on the South Fork of Workman Creek, within the Sierra Ancha Experimental Forest, about 30 miles north of Globe, Ariz. The two study sites are representative of the general physical environment on the watershed, although there are differences in recent forest history and some differences in vegetation.

Climate, Soils, and Topography

Workman Creek is characterized by cold moist winters, dry warm springs and hot moist summers (Pase and Johnson 1968). Annual precipitation averaged 34.2 ± 2.1 inches from 1956 to 1981; however, only an average of 28% (9.6 inches) falls between June and September. The watershed is inaccessible between December and April because of the heavy snow cover. Annual temperatures average 48° F, varying from 31° F in January to 65° F during July and August.

Soil parent materials in the watershed are Dripping Springs quartzite, intruded by diabase and basalt, and Troy sandstone. Surface soils are of loam and clay loam texture with granular or crumb structures. Subsoils vary from clay loams to clay. Surface soil depth ranges from 3 to 10 inches, with total depths of around 30 to 50 inches. Elevations on South Fork range from about 6,700 to 7,270 feet. Both study sites were in the upper third of the watershed. One site, an old burn, is on relatively level terrain, while the other consists of two level areas connected by a steep slope.

Vegetation

The watershed originally contained mixed conifer stands on the moister sites and pure ponderosa pine on the upper, drier areas. The mixed conifer vegetation belonged to the *Abies concolor-Pseudotsuga menziesii/ Quercus gambelii* habitat type (Moir and Ludwig 1979). Plant species in the type are white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine, and Gambel oak (Quercus gambelii) with a minor component of quaking aspen (*Populus tremuloides*) and New Mexico locust (*Robinia neomexicana*). Only a few shade-tolerant herbaceous species (e.g., Canadian violet (*Viola canadensis*)) grew under the forest canopy (Pase and Johnson 1968). The ponderosa pine sites usually contained an understory of oak and locust, and a sparse herbaceous layer. Roadside areas and natural openings, however, contained a diverse grass and forb cover. The basal area for the entire watershed was originally 201 square feet per acre.

South Fork watershed was harvested by the single-tree selection method between 1953 and 1955. Logging removed about 46% of the merchantable trees and reduced the total basal area by 24% (Rich and Gottfried 1976).

Area History

Grass Area

In July 1957, a wildfire destroyed 60 acres of predominantly ponderosa pine in the upper, southeastern part of the watershed. Although the site was relatively level, the entire burn was seeded with a mixture of 2 pounds of crested wheatgrass (*Agropyron cristatum*), 3 pounds of intermediate wheatgrass (*A. intermedium*), 2 pounds of orchardgrass (*Dactylis glomerata*) and 2 pounds of yellow sweetclover (*Melilotus officinalis*) per acre, as an erosion control measure. A good stand of grass was established by the end of the first summer (Rich 1962). Locust and oak sprouts soon dominated the site.

Site preparation for tree planting began in 1966. Most snags were felled, downed material was windrowed and burned, and chemical brush and grass control operations were started. Brush control was successful, grass control was not; both activities were stopped by 1974 (fig. 1). Grass and forb production determined by double sampling techniques has varied from 1,729 pounds per acre (37% grass) during a wet year to 700 pounds per acre (69% grass) in a dry year. Some of the most common plants were: wheatgrass, bracken fern (*Pteridium aquilinum*), bromegrasses (*Bromus* spp.), and goosefoot (*Chenopodium* spp.). The burn was planted with 2-year-old ponderosa pine seedlings during the springs of 1967, 1973, and 1974, but success was spotty. Summer drought appeared to be the primary cause of initial mortality, although losses to pocket gophers were apparent from the start of planting. Gopher-caused mortality of surviving trees became more critical after the seedlings had become established. Some gopher baiting and trapping were attempted, but because this work could not be sustained, it only produced temporary relief.

Locust Area

This 73-acre site is near the south boundary, in the upper middle section of South Fork. It is part of a 203-acre unit which supported an uneven-aged mixed conifer stand that averaged 128 square feet of basal area per acre in 1966. Seventy percent of the basal area consisted of white fir and Douglas-fir, including some large trees with diameters greater than 30 inches d.b.h. Ponderosa pine and deciduous trees made up the remaining basal area.

In 1966, the unit was cleared as part of an experimental study to determine the effects on water production of converting from a mixed conifer to a pure ponderosa pine stand. The stand was to be maintained at a density of 40 square feet of basal area per acre which was estimated to optimize overall timber and water production (Rich and Gottfried 1976). Logging slash was broadcast burned, and some areas of ponderosa pine infected with dwarf mistletoe were cleared. The area revegetated to native grasses and forbs and to New Mexico locust and oak. In 1972, slash was windrowed and brush pushed and sprayed, and the area was mechanically scarified in preparation for planting pine in 1973 and 1974.

Surveys of the planted pine indicated that while drought was the main cause of seedling mortality, gophers affected regeneration success. The site revegetated to the cover before preparation (fig. 2). The most common species in 1974 were: bracken fern, figwort (*Scrophularia parviflora*), goosefoot, thistle (*Cirsium* spp.), and wild lettuce (*Lactuca* spp.).

METHODS

Gopher Collection

Pocket gopher trapping was concentrated, but not mited, to three clusters of plots randomly distributed ithin each area. Each cluster contained three plots, ch 0.52 acres. Gophers were collected in the grass ea from June through October 1975, in April 1976, and om June through August 1976. Collections were not ade during the winter because of snow conditions. A tal of 36 gophers were trapped. Animals were grouped to four collection periods for ease of analysis and cause of the small sample size. Analysis of variance, sed on monthly averages of grasses and forbs used, incated that the group members were from similar feedg populations. Collections in the locust area were ade during the two summers.

Period	Grass area sample size	Locust area
Summer 1975	13	6
Fall 1975	12	–
Spring 1976	4	–
Summer 1976	7	4

Although total sample size is small when compared to her studies (Ward and Keith 1962), it is adequate to incate food habits and their fluctuations during snowee periods over 15 months.

Gopher stomach contents were prepared and anazed according to a modification of the technique veloped by Sparks and Malechek (1968). Ten slides ere prepared from each stomach, and contents were entified for 20 microscope fields of view on each slide. tomach contents were compared to a reference collecon from South Fork of similarly prepared plant slides.

Average percent stomach volume and percent occurnce values were calculated for each period. Percent olume calculated from the microscope field counts is

gure 1.—Grass area, in early spring, was seeded to grass after a wildfire in 1957. Grass accounted for 70% of the herbaceous cover. Snags and slash were piled and burned in preparation for tree planting.

Figure 2.—The locust area contains a forb-grass-brush cover which developed after the destruction of the original forest. Common sunflower (foreground) was one of the main pocket gopher foods in 1976.

the proportion of a food species in the stomachs and percent occurrence is the proportion of stomachs in which a species is found. The proportion of different plant parts (e.g., roots, stems, flowers) being consumed was not determined. Analysis of variance ($P = 0.05$) was used to compare gopher use of different species and species groups among and within periods.

Vegetation Sampling

Two techniques were used to sample vegetation in the primary study plots. In July 1975, percent cover was estimated by species for each plot. During the following July, sampling was done using the plotless point-quarter method (Cottam and Curtis 1956). Twenty-five randomly located points were established in each plot, and data were analyzed according to standard procedures for this method. Plant nomenclature and taxonomy followed Pase and Johnson (1968).

Individual species composition was not compared between the two years because of the sampling differences. The larger plant groups (i.e., grasses and sedges (*Carex* spp.) and forbs) were compared by Student's "t" test using percent cover and relative dominance.

Food Preferences

Pocket gopher food preferences were analyzed for summer 1976 by comparing the number of microscope fields occupied by a plant species or species group to the absolute density of the species in the vegetation sample. Preference analyses for the larger plant groups only considered species which were found in the diet. Statistical significance between species consumption and availability was determined using the technique described by Neu et al. (1974). The preference analysis for summer 1975 was limited to the larger plant groups because of the lack of specific plant density data. This

was justified because most of the key species are perennial, and their numbers would not fluctuate greatly from one year to the next.

Gopher Populations

Gopher populations were estimated by a procedure which was specific to the current effort. A value for average length of active shallow tunnel per gopher was estimated by excavating four systems and two systems on the grass area and locust area, respectively. The total length of active tunnel was determined on six, randomly located, 100-ft² subplots within each of the 18 plots. The total number of gophers per plot was calculated by dividing the length per plot by the average length per gopher value. These were converted to a per acre basis. Approximate variances of the estimates were calculated similar to Mood et al. (1974), and possible differences in population density between the two areas were assessed using the ratio of the population density difference to its estimated standard error.

Ponderosa Pine Survival

Thirty, bare-rooted, 2-year-old ponderosa pine seedlings were planted in each plot to determine mortality. Trees were planted in July 1975, during the summer rain period, and were evaluated periodically until September 1976. Mortality was attributed to drought and physiological problems (i.e., shock), to confirmed gopher activity, to unknown causes, and to winter-related problems. Missing trees were indicated as a separate category.

RESULTS

Food Habits

Grass Area

Wheatgrasses, bromegrasses, and Kentucky bluegrass (*Poa pratensis*), and grass-like species (sedges) produced 70% of the herbaceous cover on the plots during the two summers. The remaining 30% consisted of 12 forb species, mostly perennials. Four species that were identified in the gopher stomachs (i.e., pigweed (*Amaranthus* spp.), caterpillar-weed (*Phacelia magellanica*), deers-ears swertia (*Swertia radiata*), and the shrub Arizona honeysuckle (*Lonicera arizonica*)) were not found in the vegetation samples. The proportions of grasses and forbs in the total cover were more variable because of presence of New Mexico locust and Gambel oak sprouts which produced rapid growth over the year. Woody plants (e.g., New Mexico locust, ceanothus (*Ceanothus fendleri*), and Gambel oak) were 6% of the total plant cover in 1975.

Grasses were the main food for pocket gophers in this area for the first three of the four collection periods, but there was a steady decrease in their importance (table 1). Grasses were found in all of the stomachs collected from the grass area. Consumption by individual gophers varied from 99.8% to 57.3%. Use of bromegrass, primarily mountain brome (*Bromus marginatus*), was particularly high, while wheatgrasses, the most common species, were only a minor component of the diet.

Insects were a relatively large, consistent item in the diets (table 1) averaging over 10%. This is greater than the trace reported by either Ward and Keith (1962) or the 3% of Goodwin and Hungerford (1979). No attempt was made to identify insect species.

Forbs and shrubs-trees were of minor importance during the summer of 1975. The difference between forb and grass consumption was statistically significant during this period. Five forbs and one tree which were present in 1975 were not consumed.

The relative volume of grasses dropped slightly to 72% of the composite diet in the fall of 1975 (table 1). The difference between grass and forb consumption was statistically significant.

Total grass consumption in spring 1976 (table 1) declined by 16%, with a 22% drop in bromegrass. The changes, compared to summer 1975, were significant but not when compared to the previous fall. Differences between adjacent periods were not significant. Forb consumption, especially of thistle and geranium (*Geranium eremophilum*), rose in the spring from 16% to 25% of the diet (table 1), although this was not statistically different than for the previous periods. Heavy use of geranium in the spring has also been reported from Colorado (Tietjen et al. 1967). Use of grasses and forbs was not statistically different during the spring period. Although woody material was found in half of the stomachs, use of these plants continued to be minor. Burton and Black (1978) found relatively heavy gopher use of woody plants during winter in Oregon.

During the summer of 1976, grass consumption decreased to 44% of the composite diet (table 1). This was significantly less than for the previous summer or fall. Grasses continued to account for 70% of the herbaceous cover but total grass consumption was significantly less than expected (table 2). Forb consumption (48% of the diet) was significantly higher than for the first two periods (table 1) and was significantly greater than expected (table 2). Differences between grass and forb consumption during this period were not statistically significant. Three species were eaten but did not appear in the 1976 vegetation survey (i.e., mullein (*Verbascum thapsus*), caterpillar-weed, and ponderosa pine). Four species, which were present in summer 1976, were not eaten, although they were part of the diet during other periods. These were fleabane (*Erigeron* spp.) and red-and-yellow pea (*Lotus wrightii*), pigweed, and locust (table 1).

A total of 24 food items (table 1) were identified in the 36 stomachs collected from the grass area; grasses and sedges accounted for 5 items (21%), forbs for 13 items (54%), woody plants for 4 items (17%), insects and an unknown fungus accounted for the remaining 2 items (4% each). The average number of food items identified in the stomach samples varied from a high of 7.1 during summer 1976 to a low of 4.5 during the spring, reflecting the lack of food diversity at that time. Average diversity

Table 1.—Relative volume (percent) and frequency of occurrence (percent) of plant and and animal species in pocket gopher stomachs

Species	Grass area								Locust Area			
	Summer 1975		Fall 1975		Spring 1976		Summer 1976		Summer 1975		Summer 1976	
	Vol.	Occur.	Vol.	Occur.	Vol.	Occur.	Vol.	Occur.	Vol.	Occur.	Vol.	Occur.
Number of animals	13		12		4		7		6		4	
	Grass											
Bromus spp.	66.3	100	61.7	100	39.8	75	38.5	100	8.4	100	17.4	75
Agropyron spp.	6.8	62	1.2	67	1.7	25	1.5	86	8.4	67	0.4	25
Poa pratensis	1.4	100	8.5	100	15.1	25	3.8	100	1.0	33	1.6	50
Dactylis glomerata			0.9	8								
Total grass	84.5	100	72.3	100	56.6	100	43.8	100	17.8	100	19.4	75
	Grass-like											
Carex spp.			0.5	25					13.4	33	0.1	25
	Forbs											
Cirsium spp.			11.0	58	11.6	50	42.9	71			0.2	25
Geranium eremophilum			0.2	25	12.3	50	T	29	0.4	50		
Phacelia magellanica	2.6	85	0.2	42	1.1	25	1.1	86	0.2	67		
Lotus wrightii	0.1	15	T	17					T	17		
Swertia radiata	T	8	0.5	8					0.3	33		
Amaranthus spp.	T	15										
Verbascum thapsus	0.1	8	T	8			T	14	7.8	67	0.1	25
Erigeron spp.	T	8	3.8	50					31.4	83		
Lactuca spp.			0.4	25			0.9	57	1.8	17	11.3	100
Arenaria confusa					0.4	25					0.8	25
Pteridium aquilinum							2.1	43	0.5	33	3.6	100
Lathyrus graminifolius							1.3	14				
Helianthus annuus									6.3	50	36.2	00
Chenopodium spp.											0.7	50
Total forbs	2.8	92	16.1	83	25.4	100	48.3	100	48.7	100	52.8	100
	Shrubs-Trees											
Pinus ponderosa					0.1	25	0.1	29			1.6	75
Robinia neomexicana	T	8	T	8	0.1	25					0.3	25
Ceanothus fendleri	0.9	8	0.7	25	3.3	25					0.2	50
Rubus strigosus	0.2	23							1.2	17		
Sambucus neomexiana									T	17		
Rosa fendleri									T	17		
Lonicera arizonica	0.1	15										
Total shrubs-trees	1.2	39	0.7	33	3.5	50	0.1	14	1.3	50	2.1	100
	Miscellaneous											
Insects	11.5	62	7.5	92	14.5	100	7.8	86	18.8	67	15.2	100
Unknown (fungus)			2.9	17							10.4	75
Total	100.0		100.0		100.0		100.0		100.0		100.0	

T = Trace (<0.1).

during summer 1975 (5.2 species) was significantly less than during fall (6.8 species) or for summer 1976, but similar to the spring reading. Fall use was significantly different from spring use. One pocket gopher collected during the fall had eaten 10 different food items: 2 grasses, insects, sedges, 5 forbs, and ceanothus.

Locust Area

The herbaceous cover in this area consisted of 73% forb species. Sixteen species were sampled in 1975. The relative densities of wheatgrasses and bromegrasses were similar, although bromegrass was more widely distributed. Trees, shrubs, and half shrubs made up 37% of the total cover. Grasses and sedges were 18%, and forbs were 45% of the total cover.

Gopher feeding habits in the locust area were studied during the two summer periods. In 1975, forb species made up 49% of the diet (table 1). Fleabane, mullein, and common sunflower (*Helianthus annuus*) were the main species. All of the eaten forbs were represented in the vegetation sample. Grasses and sedges comprised about 31% of the diet; bromegrass and wheatgrass were eaten in equal proportions. All of the gophers had some grass in their diets. Grasses and sedges, which contributed 18% of the plant cover, were consumed in higher proportion than their availability, based on Neu

Table 2.—Gopher food preferences for the summer 1976: plant species consumption in relation to their availability for species counted in the vegetation survey and in stomach samples

	Microscope field counts					
	Grass area			Locust area		
	Observed	Expected	Sig.	Observed	Expected	Sig.
Larger plant groups						
Grass and grass-like species	645	1,123	*	146	114	
Forbs	589	111	*	425	452	
Shrubs				25	29	
Species						
Grass species						
Bromus spp.	524	246	*	127	54	*
Agropyron spp.	34	835	*	4	39	
Poa pratensis	87	42		15	9	
Grass-like species						
Carex spp.				1	21	
Forbs						
Cirsium spp.	494	2	*			
Geranium eremophilum	2	1				
Verbascum thapsus				1	12	
Lactuca spp.	26	7		110	195	*
Arenaria confusa				8	1	
Pteridium aquilinum	45	67		38	31	
Lathyrus graminifolius	22	33				
Helianthus annuus				259	149	*
Chenopodium spp.				7	101	
Shrubs-trees						
Robinia neomexicana				3	32	

* = *Significant at the 5% level.*

et al. (1974). Grass and forb consumption was statistically similar for both periods. Food habits in the locust area, however, were opposite to those of the pocket gophers in the grass area for the summer of 1975. Significantly more forbs and less grasses were eaten in the locust area. Wheatgrass utilization was similar for the two areas, but more bromegrass was consumed in the grass area.

The proportion of grasses and forbs on the area fluctuated slightly between the summers of 1975 and 1976. Twenty-eight forb species were sampled; of these, lettuce, common sunflower, and goosefoot were the most common (table 3). Shrub cover increased to 47%. The proportions of grasses and forbs eaten by gophers in the locust area did not change between the two summers. Both plant groups were eaten in proportion to their availability (table 2). Stomach analysis indicated that forbs were about 53% (table 1) of the diet in summer 1976, with sunflower and lettuce the main items eaten. Utilization of grasses and forbs was similar between the grass area and locust area during summer 1976. Insects were a relatively large component of the diet during both summers (table 1).

A total of 24 food items (table 1) were found in the gophers trapped in the locust area. This was the same number as in the grass area but there were some slight differences among the plant groups, primarily the larger variety of woody plants being used. Gophers collected during summer 1975 ate an average of 7.7 species. This indicated a more diverse diet here than for grass area gophers during summer 1975 or spring 1976. The average gopher ate 9.2 food items in 1976; a significantly greater diet diversity than existed during any of the four periods on the grass area. The large number of species used is directly related to the rich and diverse plant cover available in the locust area (table 3, fig. 3).

Gopher Populations

Measurements of active tunnel density indicated that the grass area supported a pocket gopher population (with standard deviation) of about 24 ± 7 animals per acre, and that the locust area supported a population of 16 ± 5 animals per acre. The average difference between the two areas (eight animals) was not statistically significant.

Ponderosa Pine Survival

Ponderosa pine seedling survival was poor on both areas. Only 3% of the seedlings survived until the end of September 1976 on the grass area, while 13% survived in the locust area. The difference was significant, but regeneration of both areas would be unacceptable by management criteria. Drought and related problems were the main causes of mortality on the two areas, ac-

Table 3.—Vegetation survey (percent) of study sites using plotless point-quarter technique, summer 1976

Species	Grass area				Locust area			
	Relative			Importance value	Relative			Importance value
	Density	Dominance	Frequency		Density	Dominance	Frequency	
Grasses and sedges								
Bromus spp.	19.1	11.4	20.0	50.5	5.5	1.6	6.0	13.0
Agropyron spp.	65.0	33.3	53.7	152.0	4.0	1.5	2.7	8.2
Poa pratensis	3.2	2.5	2.7	8.3	0.9	0.1	0.5	1.5
Carex spp.	0.3	0.5	0.9	1.7	2.1	11.4	2.3	15.9
Forbs								
Polygonum convolvulus	0.2	T	0.5	0.8	6.5	0.3	6.6	13.5
Lactuca spp.	0.6	0.5	1.2	2.3	19.7	2.8	17.1	39.5
Geranium eremophilum	0.1	0.1	0.3	0.5	3.5	9.4	4.0	16.8
Vicia americana					1.9	0.8	2.2	4.8
Phacelia magellanica					2.3	0.3	2.9	5.5
Helianthus annuus					15.0	5.1	13.3	33.4
Ipomoea spp.					0.5	0.1	0.5	1.1
Scrophularia parviflora					3.7	3.1	4.8	11.6
Chenopodium spp.	0.8	0.6	0.9	2.2	10.2	0.3	10.8	21.4
Pteridium aquilinum	5.3	15.7	8.8	29.7	3.1	11.5	3.8	18.4
Moldavica parviflora					0.9	0.1	1.3	2.3
Solidago missouriensis					0.2	0.1	0.2	0.4
Melilotus albus					0.2	2.5	0.4	3.1
Arenaria confusa					0.1	0.2	0.2	0.5
Melilotus officinalis	0.1	0.5	0.3	0.9	0.2	T	0.4	0.6
Verbascum thapsus					1.2	0.5	1.4	3.1
Erigeron spp.	0.1	0.1	0.3	0.5	1.0	T	0.9	1.9
Lotus wrightii	0.1	T	0.3	0.4	1.0	0.9	0.7	2.6
Oenothera hookeri					0.1	T	0.2	0.3
Lathyrus graminifolius	2.6	1.4	5.6	9.5	0.1	0.1	0.2	0.3
Monarda menthaefolia					0.1	T	0.2	0.3
Senecio spp.					0.2	T	0.4	0.6
Thalictrum fendleri					0.1	0.1	0.2	0.4
Houstonia wrightii					0.1	T	0.2	0.3
Amaranthus spp.	0.2	T	0.3	0.8	1.0	0.1	0.9	2.0
Galium aparine					0.3	0.2	0.2	0.7
Pseudocymopterus montanus	0.1	0.1	0.3	0.4				
Cirsium spp.	1.7	1.8	2.4	5.8				
Fungus					0.1	T	0.2	0.3
Woody plants								
Rubus strigosus					9.3	9.6	8.6	27.5
Robinia neomexicana	0.3	27.2	0.9	28.4	3.2	32.0	4.3	39.6
Symphoricarpos rotundifolius					1.7	5.3	1.4	8.4
Quercus gambelii	0.2	4.3	0.6	5.1				

T = Trace (<.1).

counting for 84% in the grass area and 62% in the locust area. Most drought mortality occurred during the first month on the grass area, and between August and October in the locust area. Mortality caused by gophers was equal (9%) for the two areas during the study period. However, 84% of these trees were killed in the first month on the grass area, compared to 12% for the locust area. The difference was significant. Sixty percent of the gopher-caused mortality in the locust area occurred between October 1975 and April 1976. This winter use is consistent with results reported by Burton and Black (1978). Equal winter mortality might have occurred in the grass area had more trees survived the initial establishment period.

DISCUSSION

It is common practice in some parts of the western United States to seed grasses in forested areas which have been devastated by wildfires or other natural or human-caused events. The grass area on the South Fork of Workman Creek is an example of the long-term consequences of this activity. The area now contains a vigorous herbaceous cover of 70% introduced or native grasses. This cover is detrimental to conifer regeneration because of the competition for moisture (Embry 1971), but also because it supports a relatively large valley pocket gopher population–about 24 animals per acre. This population is greater than the 0.22 animals per acre reported for an uncut ponderosa pine stand, on deep soils, near Flagstaff (Goodwin and Hungerford 1979).

Stomach analysis from animals collected during the two field seasons indicates that grasses, especially bromegrass, are an important part of the pocket gopher diet. Although the percentage of grasses decreased over the study from 84% to 44%, their importance was never replaced by forbs. The 84% value is among the highest reported for grass usage by *Thomomys* spp. in a forest

zone. All of the animals had some grass in their stomachs when trapped. At least 16 forbs were available but were generally not used heavily. The shift from bromegrass to thistle in summer 1976 is not surprising, because succulent forbs are considered the preferred food. Laboratory tests have confirmed that pocket gophers can discern preferred foods (Hungerford 1976). Preference indices and tables confirm this relationship.

The relatively large pocket gopher population on the grass area indicates that a diet dominated by grasses, particularly bromegrasses, may be nutriently beneficial. These results differ from feeding habits of *Thomomys talpoides* on mountain grasslands in west-central Colorado (Keith et al. 1959, Tietjen et al. 1967). Differences in grass species composition may influence gopher feeding preferences.

Although forbs are generally preferred by pocket gophers, substantial grass consumption has also been reported in other forest and woodland sites. Burton and Black (1978) found that grasses provided 32% of the annual diet of the Oregon pocket gopher (*T. mazama*) within a disturbed ponderosa pine site. *Bromus* also was the preferred grass on their site. However, grass consumption was lower (17%) during July when more forbs were available. Thirty-eight percent of the summer-fall *T. bottae* diet in a managed Arizona ponderosa pine forest consisted of grasses (Goodwin and Hungerford 1979). Bandoli (1981) reported that grass, primarily blue grama (*Bouteloua gracilis*), accounted for about 30% of the average annual gopher diet and averaged 36% of the summer diet on his pinyon-juniper site, although some perennial forbs were more preferred. Grass and sedge consumption averaged about 25% on the locust area. These values can be compared to the Colorado results which showed low summer-fall grass consumption of 6% (Ward and Keith 1962) and of 18% (Keith et al. 1959).

Figure 3.—The diversity of the plant cover on the locust area can be seen at this location, where the cover included ponderosa pine, locust, raspberry, sunflower, and grasses. The photograph was taken in September 1977.

Forb consumption during the two summers averaged 51% in the locust area and was 48% in the grass area during the summer of 1976. These values are consistent with others reported for *T. bottae* or for *T. mazama* on a forest site. Goodwin and Hungerford (1979) reported that 46% of the diet was forbs while Bandoli (1982) indicated consumption of at least 39%. Burton and Black (1978) reported that forbs were 40% of the annual diet and averaged 51% of the July diet. Research in the Colorado mountain grassland showed higher summer-fall forb consumption; Keith et al. (1959) reported 85%, and Ward and Keith (1962) reported 93%.

Pocket gophers killed fewer ponderosa pine trees than expected. Pine survival was statistically better in the locust area but still inadequate to restock the area. Drought and gophers killed seedlings earlier in the grass area than in the locust area. Precipitation was below average during summer 1975. Drought may be more severe under grass than under a locust-forb cover. Gottfried (1980) found significantly more soil moisture in the top 24 inches of soil under 5-year-old locust stands than in grass stands in a site near the grass area. The exact reasons for the mortality in 1975 cannot be determined, but more intensive competition for soil moisture by grasses (Embry 1971) and a slightly higher gopher population are possibilities.

ACKNOWLEDGEMENT

The authors acknowledge the valuable contribution of Paul Flowers, a former graduate student at Arizona State University, during the field phases of this study.

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Pocket gopher food habits were studied on two nonstocked forest sites. Grasses, especially bromegrass, were between 84% and 44% of the diet on the seeded grass site. Forbs supplied 51% of the diet on a site with forb-grass-brush cover. Ponderosa pine was not used heavily. High use of grasses has management implications.

Keywords: *Thomomys bottae,* valley pocket gopher, food habits, forest regeneration, Arizona

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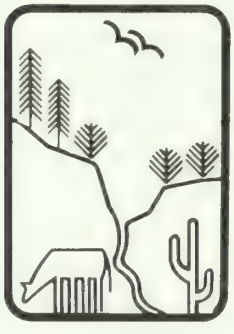

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Fort Collins,
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**Research Paper
RM-256**

Modeling Forest Scenic Beauty: Concepts and Application to Ponderosa Pine

Thomas C. Brown and Terry C. Daniel

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Abstract

Statistical models are presented which relate near-view scenic beauty of ponderosa pine stands in the Southwest to variables describing physical characteristics. The models suggest that herbage and large ponderosa pine contribute to scenic beauty, while numbers of small and intermediate-sized pine trees and downed wood, especially as slash, detract from scenic beauty. Areas of lower overstory density and less tree clumping were preferred. Moderate harvest of relatively dense stands tends to improve scenic beauty once the stand has recovered from obvious harvest effects. The recovery period can be greatly reduced by slash cleanup.

PREFACE

This paper was written for forest managers, landscape architects, and others interested in forest scenic quality. The paper presents the results of recent research directed at developing statistical models to predict the effects of changes in forest characteristics on public perception of scenic beauty. The foundation for this modeling effort is approximately a decade of research and development of methods to quantitatively assess the scenic beauty of forest landscapes. In that time, several related methods for measuring scenic quality based on public perception and judgment have been developed, tested, and successfully applied in forest management contexts. This progress in scenic beauty measurement and prediction model development has important implications for forest management and planning.

The introduction of this paper describes the place of scenic beauty modeling within forest management. The next section examines various efforts to assess forest scenic beauty. Then, the data used for this study are described. The next section presents several scenic beauty models and the procedure used to specify them. This is followed by a description of two aids for interpretation of scenic beauty estimates. Then, uses of the models are discussed, first in terms of forest management in general, and second in terms of landscape assessment and the Visual Management System. Last, some conclusions are offered. Detailed bivariate relationships among the variables are described in the appendix. The data and modeling sections are the most technical. Readers interested in an overview are directed to the management implications and introductory sections, then to the summary and conclusions, and then perhaps to the interpretation and use sections.

USDA Forest Service
Research Paper RM-256

November 1984

Modeling Forest Scenic Beauty: Concepts and Application to Ponderosa Pine

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Modeling Forest Scenic Beauty: Concepts and Application to Ponderosa Pine

Thomas C. Brown and Terry C. Daniel

MANAGEMENT IMPLICATIONS

Statistical models were developed relating the public's perception of scenic beauty to forest features. In order to develop these models, timber stands were delineated, using standard timber management criteria, in two watersheds on the Coconino National forest, in north-central Arizona. All stands were predominately of pondersosa pine, with Gambel oak mixed in throughout, and ranged from 30 to 380 square feet of basal area. Overstory, herbage, downed wood, and ground cover features were measured in selected stands, at 15 points (sites) per stand, using widely accepted forest inventory procedures. Color slides were also taken at each site, from which scenic beauty judgments were obtained. The physical measurements of forest features were then statistically related to the scenic beauty judgments.

The models show that, for ponderosa pine stands similar to the study area, herbage and large pine contribute to scenic beauty, while numbers of pulp-sized and small sawtimber-sized pine trees and downed wood detract from scenic beauty. Gambel oak of all sizes improve scenic beauty. Slash is much more detrimental to scenic beauty than natural downed wood. Lower overstory densities are preferred, as are lower degrees of tree grouping.

The models suggest that moderate harvest of relatively dense stands, such as most of those inventoried for this study, would improve scenic beauty once the stand had recovered from obvious harvest effects, and that the recovery period could be shortened considerably by slash removal. Furthermore, leaving some mature pine and avoiding heavy grazing of the herbage response to harvest would enhance scenic beauty.

The scenic beauty models are well-suited to use in forest planning. They can be used to estimate the relative scenic beauty of existing forest areas as well as to predict the impact of postulated changes in those areas given relatively modest measuration data inputs. And, because they use physical features as independent variables, they can be easily linked to physical simulation models, allowing prediction of near-view scenic effects along with more traditionally quantified forest characteristics. Furthermore, their use supplements the information available from application of the Visual Management System by providing scenic beauty estimates that are based directly on public perception and judgment, and that are mathematically related to manageable forest features.

INTRODUCTION

Public concern about the scenic beauty of outdoor environments is reflected in recent land management legislation. The Multiple-Use Sustained-Yield Act of 1960 and the National Environmental Policy Act of 1969 and associated regulations point specifically to the need to consider effects of public land management on environmental amenities, including wilderness, recreation, and esthetics. More recent legislation, the Forest and Rangeland Renewable Resources Planning Act of 1974 and the National Forest Management Act of 1976, emphasizes the need for systematic consideration of amenity resources, and specifically identifies esthetic along with wildlife, recreation, and wilderness resources.

Concern for esthetic resources has been addressed in part by the designation of special parks, monuments, and wilderness areas. The focus of this paper, however, is the substantial esthetic resources represented by the vast acreages of public lands managed under multiple-use guidelines. These lands support a wide variety of outdoor recreation activities and scenic experiences that are enjoyed by millions of visitors each year. Adequate consideration of the esthetic effects of land management alternatives for these areas requires some means for reliably determining whether esthetic quality is getting better or worse (i.e., at least an ordinal measurement capability is needed). To adequately examine "tradeoffs" between esthetic and other effects of management, a greater level of precision is necessary. In this case, interval level measurements of esthetic values are required to indicate how much esthetic quality changes with different management alternatives. Only with such precision can esthetic effects be evaluated along with more traditionally measured forest outputs (e.g., timber volume) in comparable terms.

Defining Forest Esthetics

Esthetic values (or resources) often are associated with outdoor recreation or wilderness, frequently in a way that implies they are interchangeable. At other times they are distinguished, so that esthetic resources are treated as separate from recreation or wilderness resources. In the latter case, esthetic value usually implies the scenic quality or natural scenic beauty experienced and appreciated by visitors, who may or may not be engaged in "recreation."

Esthetic experience involves a complex of environmental factors (smells, sounds, touches, and sights) and visitor expectations, goals, and feelings. A major aspect of visitors' esthetic experiences in forest environments, however, is visual. Research and management effort directed at forest esthetics (as distinguished from recreation) has principally focused on the visual characteristics of the forest environment and people's perception and esthetic judgment of the beauty of the forest landscape.

People who visit forest lands are motivated by a variety of needs, wishes, and desires, and receive a variety of physical, psychological, and spiritual benefits (Driver and Rosenthal 1982). Some visitor goals and benefits primarily relate to a recreation activity; others emphasize visual esthetic experience. A continuum of visitor interactions with the forest environment may be conceptualized. Off-road vehicle use or white water kayaking may tend to place relatively little emphasis on the visual esthetic component. The quality of hunting and fishing activities may depend somewhat more on the scenic quality of the forest setting, while hiking, camping and picnicking tend progressively to place more emphasis on visual esthetic experiences. Driving for pleasure or sightseeing depend almost entirely on the scenic beauty of the landscape.

Different individuals may emphasize activity or visual experience components more or less, regardless of the apparent character of their interaction with the environment. The same individual's emphasis may vary from visit to visit or even moment to moment during the same visit. Regardless, the scenic beauty of the forest environment probably always makes some contribution to visitor satisfaction, and in many cases is the predominant component.

The visual esthetic component is commonly referred to as "landscape quality," "visual quality," "scenic quality," or "natural beauty." Daniel and Boster (1976) and Daniel and Vining (1983) argue that "scenic beauty" best captures the meaning of the visually appreciated esthetic resources of the forest. This paper principally uses the term "scenic beauty."

ASSESSING FOREST SCENIC BEAUTY

Two recent publications classified approaches to "landscape quality assessment" (Zube et al. 1982, Daniel and Vining 1983). Both identified the "psychophysical approach" as a major direction in recent research. In the psychophysical approach, scenic beauty is conceptualized to result from the interaction between the physical features of the environment and the perceptual and judgemental processes of a human observer. That is, beauty is neither inherent in the landscape nor purely "in the eye of the beholder"; it is a product of an encounter between an observer and the landscape. This approach to landscape quality assessment requires comparisons of observers' perceptual responses to measures of landscape features for a set of different landscapes.

Zube et al. (1982) and Daniel and Vining (1983) both distinguish psychophysical models from "expert judgment" or "formal esthetic" models where emphasis is placed on landscape features, and "cognitive" or "psychological" models where observer interpretations are emphasized. The formal esthetic approach is exemplified by the USDA Forest Service (1974) landscape architects' "Visual Management System." This approach is based on the analysis by Litton (1968) of abstract formal landscape features, especially color, form, line, and texture, and their interrelationships (e.g., contrast, harmony, and variety). Focusing principally on the variety factor, professional landscape architects perform expert analyses of forest areas and classify them into essentially high, medium, and low visual quality categories (variety classes A, B, and C). Based on variety classifications and assigned categories of sensitivity (a combination of distance, duration of view, and intentions of potential viewers), management guidelines or "Visual Quality Objectives" are established. The formal esthetic approach, then, relies on an expert's analysis of both formal properties of the landscape and viewer incidence and interest. In contrast, the psychophysical approach is based on the collective esthetic judgment of groups of untrained "public" observers (i.e., a "consumer evaluation" approach) combined with empirically determined, scenically relevant landscape features.

The psychological or cognitive model is very similar to the psychophysical model, often using identical procedures to obtain indexes of landscape scenic beauty. The principal difference is in the nature of the landscape variables to which scenic quality (or preference) judgments are typically related. Psychological models emphasize meanings or interpretations assigned to landscapes rather than more direct assessments of physical characteristics. For example, the Kaplans emphasized the role of "mystery" in determining landscape preferences (R. Kaplan 1975, S. Kaplan 1975), and Ulrich (1977) suggested "legibility" as an important factor. The goal of the cognitive or psychological approach is to develop a psychological understanding (or theory) of landscape preference. The psychophysical approach has the less ambitious goal of developing the means to predict and control (manage) landscape quality. The emphasis is upon relating scenic quality perceptions to more directly and objectively measured features of the environment.

The basic psychophysical approach follows classical methods established by psychologists in the mid-19th century as they attempted to quantify relationships between changes in simple physical stimuli and human perceptual response. For example, precise mathematical relationships were developed between changes in the intensity of a light and human perception of brightness. Later, investigators applied these methods to more complex situations. Thurstone (1959) scaled esthetic qualities of several types of stimuli, and Stevens (1975) proposed a "metric for the social conscience." These and other investigators developed quite sophisticated mathematical models and analytic techniques to

measure perceptual responses and to describe psychophysical relationships. Thus, the basic approach and analytical procedures required for psychophysical assessments of landscape scenic beauty have been developed and tested for more than 150 years.

Early Research Efforts

The first studies assessing landscape quality in terms of human perception established a basic pattern that is evident in contemporary research. The typical format for psychophysical landscape studies includes three steps. First, color photographs of the landscape are shown to relevant groups of observers who express their esthetic judgment and preference by ranking, rating, or choosing scenes. Based on the observers' responses, the represented landscapes are scaled from low to high scenic quality. Second, characteristics of the landscape are measured. Finally, the measurements of the physical (used here to include biological) landscape features are related to the perceptual judgment-based indexes of scenic quality.

Shafer (1964) was among the first to suggest using color photographs and psychophysical techniques to measure the scenic quality of forest landscapes. Peterson (1967) successfully measured scenic preferences for residential landscapes using a Thurstone scaling metric. Shafer and his colleagues (Shafer et al. 1969, Shafer and Mietz 1970, Shafer and Richards 1974) went on to assess several wildland scenes and to propose a mathematical model for predicting preferences for vista scenes. These early studies, and many others at about the same period (e.g., Coughlin and Goldstein 1970, Fines 1968, Kaplan et al. 1972, Zube 1974) established that:

1. Individual human observers consistently evaluate the scenic beauty of different landscape scenes presented as either color slides or prints.
2. Scenic beauty judgments of color slides or prints adequately estimate judgments of actual landscapes.
3. There is good agreement among different observers regarding the relative scenic beauty of landscapes.

The work reported in this paper follows the psychophysical tradition. Specifically, it uses the "Scenic Beauty Estimation" (SBE) method of measuring scenic beauty, standard forest inventory techniques for measuring landscape characteristics, and statistical models to relate the two.

Measuring Scenic Beauty

Initial papers by Boster and Daniel (1972) and Daniel et al. (1973) introduced the basic features of the SBE method, and Daniel and Boster (1976) presented a more comprehensive and formal statement. They explained the foundation of the SBE method in psychological and psychophysical measurement theory, especially Thurstone categorical scaling models (Torgerson 1958, Nunnally 1978) and some principles from signal detection theory (Green and Swetts 1966).

In a typical application of the SBE method, landscape areas are represented by a systematic photographic survey (e.g., a number of randomly located, randomly oriented color slides). These photos are presented to observers who independently rate each scene using a 10-point scale. Ratings are transformed following Thurstone's procedures and the guidelines from signal detection theory to yield an interval scale index of perceived scenic beauty, the SBE. Differences in observers' use of the rating scale (e.g., low raters vs. high raters) are adjusted by the scaling procedures so that the resulting SBEs provide an unbiased measure of differences in perceived scenic beauty.

Applications of the SBE method have covered a wide range of forest scenic quality assessment problems. Initial studies focused upon the different scenic consequences of alternative watershed treatments in ponderosa pine forests (Daniel et al. 1973, Daniel and Boster 1976). The method also has been applied to northeastern (Brush 1979) and northern Rocky Mountain (Benson and Ullrich 1981) forests, where scenic effects of silvicultural methods, species composition, harvest techniques, roads, and other management changes in the forest landscape were measured. Daniel et al. (1977) developed a "scenic beauty map" of a ponderosa pine forest area by using the SBE scale to compute "contours" (isoquants) of scenic quality. The scenic effects of prescribed fires and wildfires in ponderosa pine forests were observed by Anderson et al. (1982) and by Taylor and Daniel (1984). Schroeder and Daniel (1980) used the SBE method to develop "scenic beauty profiles" for measuring the relative beauty of views offered by different forest road alignments. Daniel et al.[2] provided a comprehensive assessment of the scenic impact of mountain pine beetle damage to ponderosa pine stands in the Front Range of Colorado. These and other applications of the basic SBE methodology have demonstrated the utility of the method for assessing forest scenic resources.

Several studies have substantiated the theoretical sufficiency of the SBE method. Daniel and Boster (1976) report two tests of the reliability and validity of using color slide representations to obtain scenic beauty values for forest areas. Buyhoff and his associates (Buyhoff and Leuschner 1978, Buyhoff and Wellman 1980, Buyhoff et al. 1980) provided some of the most successful and rigorous examples of psychophysical scenic quality assessments using a paired-comparison response format, rather than the rating scale method used in the SBE method. Observer choices among pairs of landscape scenes were subjected to psychophysical

[2] *Daniel, Terry C., G. J. Buhyoff, and J. D. Wellman. 1981. Assessment of public perception and values regarding mountain pine beetle and western spruce budworm impact in the Colorado Front Range. Final Report, Cooperative Agreement No. 16-930-GR, 36 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.*

scaling based on Thurstone's (1927) "Law of Comparative Judgment." The result was an interval scaled index of the observers' preferences based on the perceived scenic quality of the scenes. They found that this metric clearly distinguished among vista landscape scenes, and that it could be used to characterize scenic beauty in prediction models, thereby accounting for most of the variance in scenic beauty of the vista scenes.

Both the SBE and paired-comparison-based indexes purport to measure perceived scenic quality. Theoretically, they should yield very similar scale values for identical scenes. This theoretical expectation was tested in two studies (Buyhoff et al. 1982, Hull et al. in press) where identical landscape scenes were independently assessed using the rating and paired-comparison procedures. Resulting ratings and choice frequencies were subjected to appropriate transformations to yield SBE values and comparative judgment indexes, respectively. The two measures produced nearly identical scalings of the landscape scenes (correlations between the two scales were all greater than 0.90).

These same studies also provided a test of context stability, both with regard to the landscapes being assessed and the observers making the judgments. Observer groups represented general public populations (church and civic organizations) and college students in Arizona and Virginia. Paired-comparison groups saw only the 16 forest scenes involved in the theoretical tests, while SBE observers rated the 16 scenes randomly interspersed among more than 100 other similar scenes. None of these context differences produced significant degradation of the relationship between the SBE and paired-comparison metrics.

Near-View Scenic Beauty Prediction Models

Shafer et al. (1969) were the first to statistically relate public preference judgments of forest scenes to the physical features in the scenes. They studied vista scenes and measured the independent variables directly on the photographs of the scenes. Studies of near-view scenes and measurement of independent variables on-site, the focus of this paper, came later.

Daniel and Boster (1976) were the first to statistically relate public preferences for near-view forest scenes to physical features of the scenes. Using the SBE method of characterizing scenic beauty, they demonstrated that different harvest treatments produced different scenic beauty values in what were initially very similar ponderosa pine stands. These treatments differed in both overstory and ground cover manipulations, which suggested that these factors were important determinants of perceived forest scenic quality. Daniel and Boster (1976) reported relationships between SBEs and measures (judged from color slides) of forest density, tree size, vegetative ground cover, and amount and distribution of slash and downed wood. For example, stand density correlated 0.74, tree diameter correlated 0.73, and the amount of downed wood correlated -0.87 with SBE values.

Arthur (1977) used multiple regression analysis to develop the first models for predicting near-view scenic beauty based on vegetative characteristics of forest scenes. Individual color slides of ponderosa pine forest sites were subjected to observer rating and SBE scaling. The same slides were presented to two forest silviculturists familiar with the areas, who estimated values for several forest mensuration variables, including stand densities, tree size distributions, and downed wood volumes. Multiple regression models based on these mensuration variables explained 76% of the variance in SBE values, showing considerable precision in predicting the SBEs obtained for the slides. These models, and several others reported by Arthur (1977), confirmed that near-view response models could be developed and could be useful in managing forest areas where scenic quality effects were of concern.

Daniel and Schroeder (1979) and Schroeder and Daniel (1981) presented models based on direct field inventories of forest characteristics for many sites in northern Arizona and the Front Range region of Colorado. Each site was directly inventoried using conventional forest mensuration procedures to obtain estimates of overstory stand structure (e.g., stems per acre in 4-inch size classes), downed wood sizes and volumes (cubic feet per acre in several size classes), and vegetative ground cover (pounds per acre of grasses, forbs, and shrubs). For the Arizona sites, SBE values were based on observer judgments of eight color slides taken within each of 94 approximately 1-acre-sized forest sites. A number of aggregations and combinations of the independent (mensuration) variables were investigated, and several multiple regression models were developed for different subsets of the forest sites (e.g., sites with up to 40%, up to 60%, and up to 90% of the overstory in ponderosa pine). In all cases, final models accounted for more than 50% of variance in SBE values.

To test generalizability, Schroeder and Daniel (1981) applied the Arizona models to 40 independently assessed sites in the Boulder Canyon area, northwest of Denver, Colo. Because direct application of Arizona models was not successful, they developed similar models for the Colorado sites. Principal differences included adjustments of coefficients for variables common to both sets of models and the addition of insect damage variables in the Colorado models. The Boulder Canyon sites were selected for a study of the scenic impacts of the mountain pine beetle outbreak in the Colorado Front Range; the Arizona sites had no noticeable insect damage or mortality.

Further developments in scenic beauty modeling continue. Schroeder and Brown (1983), using the same data as that reported in this paper, tested the utility of nonlinear and interaction terms in regression models of near-view scenic quality, and found that such terms generally added little to simple linear terms in predictive capability.

Second, approximately 200 sites in the Colorado Front Range have been used to develop models sensitive to mountain pine beetle impacts (Daniel et al. 1981). These models have been incorporated into a comprehensive

computer-assisted system for projecting the socioeconomic impacts of insect damage and insect-targeted forest management actions. The Integrated Pest Impact Assessment System (Daniel et al. 1983) includes models for predicting the scenic consequences of alternative insect and forest management plans.

The potential utility of near-view scenic beauty response models is well documented by previous research. More extensive tests were needed, however, to examine the importance of mensurational variables not previously considered, to investigate the utility of separate models for preharvest and postharvest conditions, and to test the utility of near-view models in the context of operational scale forest management problems. In addition, the characteristics of a general near-view model for Southwestern ponderosa pine needed to be described. Finally, the meaning of the scenic beauty values provided by the models had to be more precisely described than it had been in previous papers; and the potential role of such models in national forest management, and the relationship of the models to the Visual Management System, needed to be described. This paper addresses these needs.

STUDY AREA AND METHODS

The psychophysical approach to modeling near-view forest scenic beauty combines environmental perception and judgment information (the dependent variable) with standard forestry and rangeland information (the independent variables). This section briefly reviews the study area and field inventory procedures and then decribes the dependent variable and data sets. Bivariate relationships between the variables are described in some detail in the appendix, with a focus on intercorrelation and nonlinearity.

Study Area

The principal data for this paper were collected on Woods Canyon (12,000 acres), and Bar-M (16,360 acres) Watersheds, approximately 40 miles south of Flagstaff, Ariz., in the northern part of the 275,000-acre Beaver Creek Watershed, on the Coconino National Forest (fig. 1). The Woods/Bar-M area ranges in elevation from 6,400 feet in Woods Canyon to 7,740 feet at Gash Mountain. Slopes average about 10% and rarely exceed 40%. The area is predominantly forested with ponderosa pine, with Gamble oak interspersed throughout and alligator juniper interspersed at lower elevations. Bedrock underlying the area consists of igneous rocks of volcanic origin. Soils are mostly residual and less than 4 feet deep, and consist of the Siesta-Sponseller series and the heavier Brolliar series (Williams and Anderson 1967). New Mexican locust grows on the Siesta-Sponseller soils. Arizona fescue and mountain muhly are the dominant grasses under the ponderosa pine canopy in both soil types; but, pine dropseed, black dropseed, June grass, and squirreltail are also common. The area had been selectively

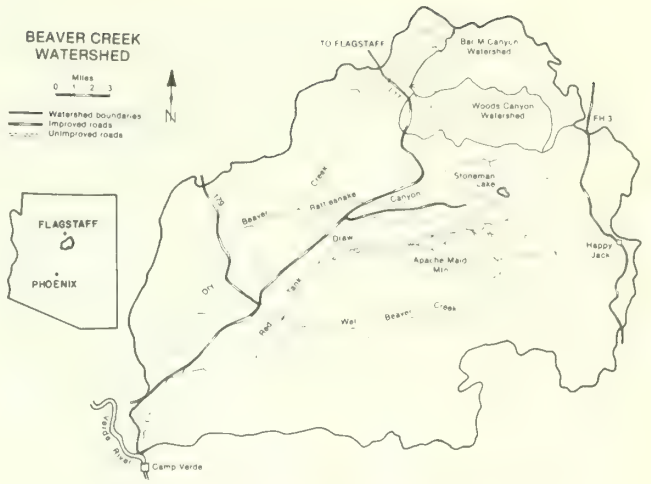


Figure 1.—Woods Canyon and Bar-M Watersheds.

harvested about 30 years before this study, but few signs of that harvest remained, giving the area a generally unmanaged appearance.

Timber stands of at least 10 acres of like density (crown closure), tree distribution and grouping, tree height, and crown size were delineated on aerial photos of the Woods/Bar-M area. Six percent of the stands were pole timber stands, 17% were sawtimber stands, and 76% were mixed sawtimber and pole timber stands. Forty-nine percent were from 40% to 70% crown canopy, and 34% were of greater than 70 percent crown canopy.

Inventory Procedure

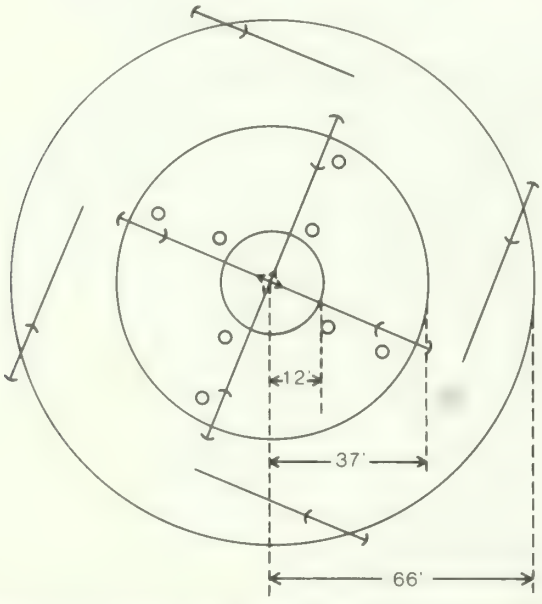
Twenty-three of the delineated stands were inventoried in 1979, before the recent harvest. These stands were selected in a quasi-random fashion, with consideration given to accessibility and the predetermined logging schedule. The proportion of preharvest stands inventoried in each stand type and crown canopy class reflected the full distribution of stands in the Woods/Bar-M area. Four of the 23 stands were reinventoried in 1980 (after sawtimber harvest, but before any slash treatment) and again in 1981 (after pulpwood was additionally harvested and slash was piled). The postharvest inventories do not proportionally represent the entire Woods/Bar-M area. The modeling results presented are based on these preharvest and postharvest inventories.

The inventory period each year was from late-May until mid-August. Stands were inventoried around 15 equidistant sample points located along lines placed to avoid sampling bias associated with topographic or drainage characteristics of the stands. The sample points were always placed at least 1 chain within the stand and at least 2 chains apart. In this paper, the specific location of the inventory point is termed a "point," and the area around the point, where the forest characteristics were measured, is termed a "site." The layout of the site inventory procedure is depicted in figure 2.

Upon arriving at a sample point, the inventory crew first chose a random compass direction from a 1 to 360 random number table and took a color slide in that direction and 90°, 180°, and 270° from the selected random direction. Photos were taken on ASA 64 film using a 35-mm camera with a 55-mm lens. On flat ground, the camera aim was parallel to the ground. On slopes, the camera was tilted up or down to accommodate the terrain. Branches hanging so close to the lens as to present focusing problems were held back as not to interfere. In some cases, the photographers needed to move a few feet to the left or right to avoid a serious obstruction to the view. All photos were taken from 8:00 a.m. to 4:00 p.m., when the sun was high enough to provide sufficient light and not cause excessive shadows. Care was taken to not include people, wildlife, vehicles, or equipment in the photos. None of the photos include buildings or other structures. Dirt roads and barbed wire fences are only occasionally visible.

Physical characteristics were measured using common forest and range inventory techniques. Seedlings and saplings were tallied by species in a 0.01-acre plot centered at the point (fig. 2). Larger trees were tallied by species, using a 10-factor prism. Crown canopy was measured by averaging four readings of a crown canopy densiometer. Stumps were tallied in a 0.1-acre plot. Tree stories and tree grouping were recorded according to the procedure outlined by Patton (1977).

Herbage and ground cover measurements were taken on eight 9.6-square-foot plots located around the point (fig. 2). Herbage was measured for three species groups: grasses, forbs, and shrubs. Daubenmire's (1959) procedure was used for herbage canopy. Height of the tallest plants was measured. Herbage weight was estimated, and herbage in one of the eight plots, randomly chosen, was clipped, dried, and weighed. Ratios of estimated to dry weight were calculated for each estimator each month and were used to adjust field estimates to dry weight estimates (Pechanec and Pickford 1937). Percentage of ground cover in gravel, cobble, stone, bare soil, litter, downed wood, herbage, and trees was estimated. For each of these herbage and ground cover variables, estimates for the eight plots were averaged to yield a site estimate. Also, the percentage of mechanically disturbed area (e.g., skid trails) in a 66-foot radius plot centered at the sample point was estimated.



. Center point (10-factor tally, crown cover)
> Photographs from center point
o 9.6 ft² plot (ground dover, herbage weight, herbage canopy, herbage height)

Downed wood transect, showing the first 12 feet in parentheses

12-foot radius plot (seedlings)
37-foot radius plot (tree stories, tree grouping, stumps)
66-foot radius plot (mechanical disturbance, brush piles)

Figure 2.—Inventory site layout.

Brown's (1974) procedure was followed in taking downed wood measurements along eight 40-foot transects located around the point (fig. 2). Measurements for the eight transects were averaged to yield site estimates of downed wood volume by size, creation (natural or slash), and condition (sound or rotten) classes, percentage of the small downed wood which harvest created, and fuel depth. Finally, number of brush piles, at least 5 feet in diameter, within the 66-foot radius plot were tallied. Site index (Minor 1964) was measured for seven site trees scattered throughout each stand. The seven measurements were averaged to yield an estimate of stand site index which was assigned to all sites in the stand.

Scenic Beauty

The slides taken at each sample point were shown to groups of at least 25 observers who rated the slides for scenic beauty on a 10-point scale. Twenty-five "base area" slides, which are slides common to all slide presentations, were evenly spaced among the 130 slides rated in each session. The base area slides were taken in Woods Canyon before the recent harvest at points other than those which received the full inventory.

For practical reasons, slides were shown in two contexts. Preharvest slides were shown in sets exhibiting no evidence of recent harvest. Postharvest slides (harvest occurred within 2 years and effects of harvest, such as slash piles, were obvious) were shown in slide sets containing about one-half recent harvest slides and one-half preharvest. The preharvest slides shown in the mixed preharvest and postharvest context were from ponderosa pine forests similar to the Woods/Bar-M area. Thus, in a given slide rating session, observers saw the 25 preharvest base area slides plus 105 slides unique to each group consisting either of only preharvest slides or of an equal mixture of preharvest and postharvest slides.

Slides to be shown in a session were scrambled into a random order and loaded into slide trays. The instructions in figure 3 were read to the observers; but, no other information was given prior to judging the slides. The first one-half of the slides were shown for 8 seconds, and the second half for 5 seconds, which has been found to be sufficient time for observers to view the slide, record a judgment on a sense-mark sheet, and

prepare for the next slide. After all slides of a given session had been shown, participants' questions about the study were answered.

The ratings were scaled using the "by slide" procedure developed by Daniel and Boster (1976). Ratings of each subject group were converted to a set of standardized (Z) scores, one per slide, based on the frequency distribution of ratings for all observers for that slide. This follows Thurstone's theory of categorical judgment (see Torgerson 1958) and adjusts groups' scores to a common interval size based on rating variances. The mean of the standardized scores of the base area slides (B) for each group was then subtracted from the standardized score for each other slide the group rated to yield a standardized difference (from B) for each slide. This procedure, taken from signal detection theory (Green and Swetts 1966), adjusts groups' scores to a common origin. The scaling procedure yields an interval scale measure of scenic beauty, and allows the judgments from two or more groups of observers to be combined. The origin-adjusted standardized scores were multiplied by 100 to eliminate decimals, and called "SBEs." Any slide having a positive SBE was preferred to an average slide from the base area; slides having negative SBEs represent scenes preferred less than the base area.

Approximately 50 sets of slides were shown to observer groups in the course of obtaining ratings for all Woods/Bar-M slides. Most of the groups comprised student volunteers from introductory psychology classes at the University of Arizona; 10 were extracurricular student groups, and 10 were church and civic groups. All of the groups are considered general public groups, because they do not represent any particular outdoor or natural resource management interest.

I am going to read some standardized instructions, so that everybody participating in these experiments will have the same information.

Today, more than ever, prudent management of wildlands such as our national forests is very important. Many wildland researchers are conducting investigations on the effects of alternative vegetative management procedures. Included among these effects are the scenic impacts of various management practices. In this research, we are attempting to determine the public's esthetic or scenic perception of such management alternatives, and we greatly appreciate your time in this effort.

We are going to show you, one at a time, some color slides of several wildland areas. Each scene represents a larger area. We ask you to think about the area in which the slide was taken rather than about the photographic quality of the individual slide.

The first slides will be shown very quickly, just to give you an idea of the kinds of areas you will be evaluating. Try to imagine how you would rate these slides, using the "rating response scale" at the top of your scoring sheet. Note that the scale ranges from one, meaning you judge the area to be very low in scenic beauty, to ten, indicating very high scenic beauty.

Then, after these initial slides, I will announce that you are to begin rating the next set of slides. You should assign one rating number from one to ten to each slide. Your rating should indicate your judgement of the scenic beauty represented by the slide. Please use the full range of numbers if you possibly can and please respond to each slide. Are there any questions? (Answer any questions by repeating instructions, or deferring them until after the experiment is over.)

These are the preview slides--do not rate these slides, just use them to get an idea of the range of areas you will see. (Show the preview slides.)

Now, rate the following slides, using the one to ten rating scale. A number will appear where the X is now to help you keep track of which slide is being shown. (Show tray one, at 8 seconds per slide.)

I am going to change slide trays now--these slides will be shown at a slightly faster rate so that we can finish sooner. (Show tray two at 5 seconds per slide.)

That is all of the slides.

Figure 3.—Instructions to subjects for rating slides.

The agreement among groups was checked by comparing SBEs for the base area slides. Pearson's correlations of one group's SBEs for the base area slides to another group's SBEs for identical base area slides ranged from 0.61 to 0.94, with a median of 0.84. Most of the correlations ranged from 0.80 to 0.90. Less than perfect (1.0) agreement is attributed to differences in esthetic perceptions among individuals in the groups and contextual differences introduced by the unique (non-base area) slides shown to the various groups. Psychology student groups could not be distinguished from extracurricular student groups, and student groups could not be distinguished from church and civic groups, in terms of the base area correlations. This confirms earlier findings (Daniel and Boster 1976, Buyhoff et al. 1982) that student volunteers adequately represent the general public for these types of studies.

The four SBEs representing the four slides taken at each point were averaged to yield the site SBE. Of the 345 sites inventoried before harvest in the 23 stands, 12 sites were eliminated because of unacceptable slide quality. SBEs for the remaining 333 preharvest sites ranged from −83 to 122, averaged 16, and had a standard deviation of 36. Preharvest site-level results for the Woods/Bar-M area, presented in the following sections, are based on data from these 333 sites.

SBEs for 120 sites inventoried in the recently harvested stands ranged from −48 to 93, averaged 9, and had a standard deviation of 31. Note that harvest effects were not obvious at all of the 120 sites. Postharvest results for the Woods/Bar-M area, presented in the following sections, are based on data from these 120 sites.

Figure 4 shows two locations typical of the Woods/Bar-M area viewed in the three consecutive inventory years. The 1979 photos show the locations before harvest, and the 1980 and 1981 photos show the locations at stages during the harvest and slash cleanup process. The SBEs for the 1979 photos were obtained in the preharvest slide presentation context, while the SBEs for the 1980 and 1981 photos were obtained in the mixed preharvest and postharvest slide presentation context. Note that the orientation of these photos changed slightly from one year to the next.

MODELS OF SCENIC BEAUTY

Many different models relating scenic beauty to physical characteristics could be developed, given the data available for the Woods/Bar-M area. Such models could differ in terms of independent variables included, equation form, and statistical model and criteria. In selecting the models presented below, the objective was to provide practical models for use in forest management. Thus, the models were restricted to variables of physical characteristics for which estimates are more likely to be available to forest managers, and contained only those variables that explained the major portion of the

View 1

View 2

B

SBE = 47

SBE = 33

D

SBE = 1

SBE = −40

F

SBE = 30

SBE = 14

Figure 4.—Changes with harvest and slash cleanup activities for two views.

variance in SBE. For additional models, see Brown (1983).

Examination of the correlations between SBE and measures of overstory, understory, and downed wood showed obvious differences between slides shown in the preharvest context and slides shown in mixed preharvest and postharvest context. For example, the site-level correlations of SBE to measures of total basal area, degree of tree grouping, herbage weight, and percent slash change from −0.26, 0.44, 0.58, and −0.11 for the slides shown in the preharvest context to 0.07, −0.07, 0.23, and −0.47, respectively, for the slides shown in the postharvest context. It is not known whether these relationships would change if the slides were shown in other slide presentation contexts. Because of the possibility of a significant slide presentation context effect on the relationship of SBE to measures of physical features, separate preharvest and postharvest models were developed.

The coefficients of the models presented were estimated using least squares regression. A three-step procedure was followed to develop the models. The first step was the selection of the variables to be subjected to the regression procedure. Initially, very detailed independent variables, such as the volume of sound natural downed wood from 6 to 9 inches in diameter, were examined. In some cases, variables that contributed very little to the prediction of SBE, such as the stump variables and most of the oak variables, were deleted. In other cases, where two variables were strongly intercorrelated and contributed similarly to the prediction of SBE (such that they did not each make an independent contribution to explanation of SBE), the variable of the pair that was less likely to be available to managers was deleted. For example, the percentage of ground cover in herbage was dropped because it served as a surrogate for herbage weight, a more frequently available measure. In still other cases, detailed variables were combined across species, size, and condition distinctions into more comprehensive variables. Combinations were based on factor analysis results and practical considerations, such as similarity of the variables from an ecological standpoint. For example, grass, forb, and shrub weights were combined to form the variable PDTOT (total herbage weight in pounds), and numerous downed wood size and condition classes were combined to form the variable DWVTOT (total downed wood volume). Finally, the remaining variables were arranged into groups for submission to regression procedures. Nonlinear terms were added to the groups for those variables that showed any nonlinear relationship with SBE. Interaction terms, however, contributed little and were not included.

The second step was the use of stepwise multiple regression to specify the models given the groups of available independent variables. All variables in the final models have an F-level of at least 4.0, a rather restrictive procedure designed to limit the number of included variables in the final models. The fact that an available variable was not included, given the entry criterion, does not imply that it is useless in predicting SBE. It only indicates that, given the F-level for inclusion/deletion, the set of included variables does a better job of accounting for the variance in SBE than any other set from the same group.

The third step was the examination of residuals depicting the variance in SBE not explained by the included variables, for model bias, and the respecification of the models where necessary.

Regression is useful for specifying prediction models and for interpreting the relationship between the dependent and independent variables. The coefficients of the independent variables in a regression model indicate the contribution of that variable to changes in the dependent variable, given that the other independent variables in the equation are controlled for, in effect by being held constant. If a variable is not included, either because it was not available or because it did not meet a stepwise entry/deletion criterion, its effects on the included variables are not controlled for, and the coefficients of the included variables reflect both their individual effects on the dependent variable and the effect of the omitted variable on the dependent variable via the intercorrelation of the included and omitted variables. Generally, stepwise regression models based on relatively restrictive entry/deletion criteria, such as those presented here, are efficient in terms of data requirements, because they avoid inclusion of highly intercorrelated variables; but such coefficients must be interpreted with caution because of the effects on those coefficients of omitted variables. However, for the Woods/Bar-M area, models not restricted by the entry/deletion criterion, such that more variables entered the equation, accounted for little additional variance (about 0.05 in terms of R^2), and had little effect on the coefficients of the variables in the more data-efficient models.

Preharvest Site-Level Models

Three preharvest models based on site-level data are presented here—the basic model, the detailed downed wood model, and the summary variable model (table 1). The basic model resulted from a stepwise regression with the following independent variables available: numbers of ponderosa pine per acre in the sapling (PPSAP), pulp and small sawtimber (PP516), intermediate sawtimber (PP1624), and large sawtimber (PP24PL) size classes, herbage weight per acre (PDTOT), and downed wood volume per acre (DWVTOT), plus nonlinear terms for each of these. The nonlinear terms were chosen from a set of several tested with bivariate regression. For example, herbage weight was taken to the 0.75 power (PDTOT75). The solution included all linear terms except PP1624, plus one nonlinear term:

$$\begin{aligned} SBE = & -16.34 - 0.0087PPSAP - 0.0281PP516 \\ & + 0.9246\ PP24PL - 0.3546\ PDTOT + 2.6896 \\ & PDTOT75 - 0.0036\ DWVTOT. \end{aligned} \quad [1]$$

The coefficients of the model are listed in table 1 along with (1) statistics describing, for the data set, the independent variables in the equation and (2) summary

Table 1.—Preharvest site-level scenic beauty models.[a]

Terms in the equations							Models[b]					
				Range		R^d with	Basic		Detailed downed wood		Summary variable	
Description	Name	Mean	SD[c]	Min	Max	SBE	Coef[e]	Beta[f]	Coef	Beta	Coef	Beta
Ponderosa pine (trees/acre)												
Saplings	PPSAP	179.3	341.4	0	2600	−0.15	−0.0087	−0.08	−0.0094	−0.09		
5-15.9 inches d.b.h.	PP516	167.6	145.8	0	739	−0.39	−0.0281	−0.11	−0.0197	−0.08		
≥24 inches d.b.h.	PP24PL	3.5	4.0	0	18	0.24	0.9246	0.10	0.7879	0.09		
Herbage weight (lb/acre)												
Total	PDTOT	86.6	90.5	1	1025	0.58	−0.3546	−0.89	−0.3025	−0.76		
$(Total)^{0.75}$	PDTOT75	26.3	19.3	1	181	0.63	2.6896	1.43	2.3635	1.26		
Downed wood (ft^3/acre)												
Total	DWVTOT	1277.3	1001.4	57	6582	−0.25	−0.0036	−0.10				
0-¼ inch diameter	DWV014	10.7	6.0	1	37	−0.44			−0.9639	−0.16		
>3 inch diameter	DWV3PL	1086.7	971.6	0	6301	−0.24			−0.0036	−0.10		
Basal area (ft^2/acre)												
Pine	PPBA	124.9	63.3	20	322	−0.37					−0.1117	−0.20
Oak	GOBA	18.8	25.9	0	187	0.17					0.2288	0.16
Tree grouping[g]	TG	2.2	0.9	1	4	0.44					11.7268	0.31
Aspect[h]	ASPECT	5.0	2.3	1	9	−0.38					−3.9753	−0.26
Constant							−16.34		−3.46		−8.01	
Model summary statistics												
R^2[i]							0.49		0.51		0.33	
Adjusted R^2							0.48		0.50		0.32	
F-level[j]							52.42		48.52		40.86	
Standard error							26.10		25.62		29.79	

[a] *Based on 333 cases.*
[b] *All variables have an F-level ≥ 4.00 and are significant at the 0.01 probability level.*
[c] *Standard deviation.*
[d] *Pearson's correlation coefficient.*
[e] *Regression coefficient.*
[f] *Standardized regression coefficient, or beta weights, result when the quantities for the variables are expressed in standard deviations from the mean of the variables. A high absolute value for a beta indicates that scenic beauty is relatively sensitive to changes in that variable within the range of the variable for the data set.*
[g] *An ordinal variable with a range from 1 to 4 (1 = trees in groups with many interlocking crowns, 2 = some tree grouping but little interlocking of crowns, 3 = very little tree grouping, 4 = no tree grouping, trees evenly spaced, see Patton 1977).*
[h] *An ordinal variable having a range from 1 to 9 (1 = flat, 2 = N, 3 = NW, 4 = NE, 5 = W, 6 = E, 7 = SW, 8 = SE, 9 = S) whereby SBE decreases as aspect increases.*
[i] *Coefficient of determination. An R^2 of 1.0 indicates that the model accounts for all of the variance in SBE.*
[j] *All three models are highly significant ($P < 0.001$)*

statistics about the overall model. The absence of intermediate sawtimber-sized pine (PP1624) from the equation should not necessarily suggest that pine trees in this size range are unimportant for predicting scenic beauty. Rather, they are relatively unimportant, and add so little to the prediction, once the other tree, herbage, and downed wood variables are in the equation, as to make the inclusion of PP1624 of little consequence for this data set.

The SBE for any specific forest location similar to those in the data set used to build the model can be estimated by simply adding the constant and the products of the coefficients multiplied by the quantities for the corresponding variables. For example, if the location for which an SBE were desired contained 100 ponderosa pine trees per acre from 5 to 16 inches d.b.h., that term would contribute −2.81 (−0.0281 × 100) to the summation. The separate coefficients indicate the change in SBE caused by a one-unit change in corresponding independent variables. For example, the addition of one 24-inch pine tree per acre would add 0.92 SBE unit.

The basic model accounts for about one-half of the variation in SBE (R^2 is 0.49, table 1) and is significant ($p < 0.001$). The adjusted R^2, which takes into account the loss in statistical degrees of freedom as more variables are added to the equation, is nearly as high, at 0.48. (Hereafter, only unadjusted R^2s are reported in the text. The unadjusted R^2s are very similar to the adjusted R^2s, which are presented in the tables.) The standard error of the estimate (i.e., the standard deviation of the actual SBE values from the predicted SBE values) is 26.1 SBE units. If the actual SBE values are assumed to be normally distributed about the predicted values, then about 68% of the actual SBEs would fall within ±26 SBE units of the predicted SBE.

The changes in SBE with changes in the independent variables are plotted for the basic model in figure 5. The

horizontal axis in figure 5 measures changes in the independent variables, which vary over their full range in the data set (table 1). For example, the number of ponderosa pine saplings (PPSAP) ranges from 0 to 2,600. Thus, keeping within that range, the most PPSAP could detract from SBE is 23 units (2600 × −0.0087). Similarly, PP516 and DWVTOT can detract at most 21 and 24 SBE units, respectively, and PP24PL can enhance SBE by at most 17 units. The most that herbage weight can enhance SBE is about 124 units, which occurs both at 1,025 pounds per acre, the maximum case for the data set, and at 1,047 pounds per acre, the point at which the herbage curve (fig. 5) reaches a maximum.

The detailed downed wood model resulted from a stepwise solution, given an available set of independent variables identical to that for the basic model, except that total downed wood volume (DWVTOT) was replaced by variables describing downed wood volume in the less than ¼-inch (DWV014), ¼- to 1-inch, 1- to 3-inch, and greater than 3-inch (DWV3PL) diameter classes, and the percentage of downed wood which harvest created. The resulting equation includes seven independent variables (table 1):

$$\begin{aligned} SBE = {} & -3.46 - 0.0094\,PPSAP - 0.0197\,PP516 \\ & + 0.7879\,PP24PL - 0.3025\,PDTOT + 2.3635 \\ & PDTOT75 - 0.9639\,DWV014 - 0.0036 \\ & DWV3PL. \end{aligned} \qquad [2]$$

In the model, downed wood and small ponderosa pine variables detract from scenic beauty, while large pine and herbage variables contribute to scenic beauty. The substitution of DWV014 and DWV3PL for DWVTOT in the model improves the overall predictive capability of the model somewhat, signified by the increase in R^2 (to 0.51) and decrease in standard error (to 25.4), compared with the basic model. The substitution also indicates the importance to scenic beauty of small diameter downed wood. Scenic beauty is more sensitive to volume of small diameter downed wood (DWV014) than to the volume of larger diameter downed wood (DWV3PL). Again, however, scenic beauty is far more sensitive to changes in herbage weight than to changes in the overstory and downed wood variables.

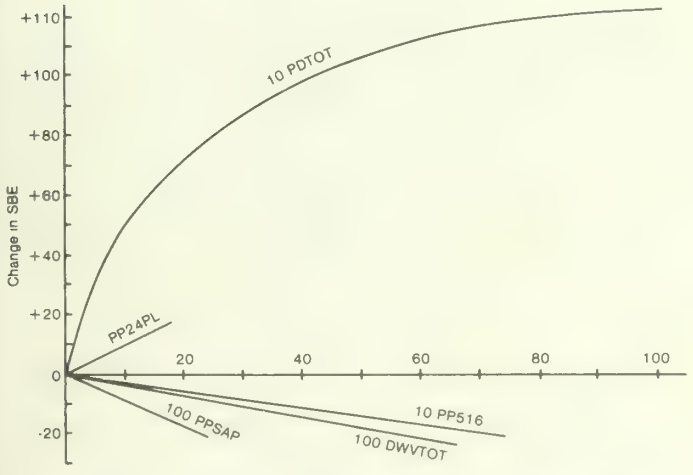


Figure 5.—Change in SBE with change in independent variable for preharvest basic model.

The summary variable model resulted from a stepwise solution, given a set of available independent variables including slope, aspect (ASPECT), site index, tree grouping (TG), tree stories, crown canopy, ponderosa pine basal area (PPBA), and Gambel oak basal area (GOBA). The resulting equation contains four independent variables (table 1):

$$\begin{aligned} SBE = {} & -8.01 - 0.1117\,PPBA + 0.2288 \\ & GOBA + 11.7268\,TG - 3.9753\,ASPECT. \end{aligned} \qquad [3]$$

In this model, oak basal area contributes to scenic beauty; pine basal area detracts. This follows from the fact that numbers of oak of all sizes are positively correlated with SBE, while numbers of pine smaller than about 20 inches d.b.h., which make up the majority of pine based area, are negatively correlated with SBE. Movement from a south to north aspect improves scenic beauty. And, a decrease in degree of tree grouping and interlocking of crowns, and corresponding increase in evenness of tree spacing, contributes to scenic beauty. Scenic beauty is most sensitive to changes in the tree grouping and aspect variables. The model is highly significant, but accounts for only 33% of the variance in SBE.

The summary variable model contains no variables directly measuring herbage or downed wood. The intercorrelations, however, suggest that herbage at least is represented indirectly, via the relationship of herbage to the summary variables. The correlations of PDTOT to PPBA, GOBA, TG, and ASPECT are −0.36, 0.26, 0.39, and −0.27, respectively, indicating that more herbage is found in less dense pine areas, in areas of more oak, in areas of less tree grouping, and on the wetter, north-facing slopes.

In both the basic and detailed downed wood models, large pine (PP24PL) and herbage contribute to increased scenic beauty. In practice, an increase in overstory will reduce potential herbage production. Thus, there is a tradeoff between these two characteristics. Figure 6 shows isoquants expressing this tradeoff, assuming mean quantities (table 1) of the other variables for the basic model. The curves are slightly convex to the origin, as a result of the decreasing marginal contribution to scenic beauty of increasing amounts of herbage. However, because the model contains no interaction terms, the isoquants would have the same shape no matter what quantities of the other variables were assumed. Only the SBE values of figure 6 would change if different quantities of the other variables were assumed.

The dotted isoquants of figure 6 assume very little herbage. Given this situation, one mature pine tree contributes about the same to pre-harvest scenic beauty as 1 pound of herbage. For example, 17 large pine trees, 5 large pine trees and 10 pounds of herbage, or 16 pounds of herbage, would result in an SBE of −11. The solid isoquants of figure 6 assume at least 300 pounds of herbage, plus mean quantities of smaller pine and downed

wood variables. Given this situation, one large pine tree contributes about the same to scenic beauty as 8 pounds of herbage. For example, given an initial endowment of no mature pine and 300 pounds of herbage plus mean quantities of the other variables, the addition of 5.4 mature pine trees or 42 pounds of grasses and forbs would result in an SBE of 65. The slopes of the isoquants continue to flatten as more herbage is initially assumed, and as more is added.

Similar isoquants could be drawn involving other variables. For example, there is a tradeoff between additional pine saplings (PPSAP) and additional pulp and small sawtimber pine trees (PP516), given some initial quantities of all variables. However, care must be used in interpreting such relationships. For example, consider the dotted isoquants in figure 6. They suggest, as stated, that about one mature pine tree can be traded for 1 pound of herbage, given that very little herbage is present. However, it is doubtful that 1 pound of herbage per acre would even be noticed. The data upon which the models were based show large variation in SBE for sites with very little herbage. The rather strong overall relationship between herbage weight and SBE ($R = 0.58$) is heavily influenced by the very clear relationship for sites with greater quantities of herbage. Thus, there should be greater confidence in tradeoffs based on a greater initial endowment of herbage, such as those demonstrated by the solid isoquants of figure 6. There, greater changes in herbage weight per large pine tree are involved, and the relationship between herbage and scenic beauty is quite clear given the data.

For both the basic model and detailed downed wood model, the effect of herbage on scenic beauty is far greater than the effect of the other independent variables. In fact, for the basic model, within the bounds of the data, only PDTOT can have a greater effect on SBE than the standard error of the model of 26 SBE units. Similarly, for the detailed downed wood model, only PDTOT and DWV014 can have a greater effect on SBE than the standard error for that model of 25 SBE units. These relationships apply, of course, only to areas depicted by the Woods/Bar-M preharvest data set, which include only treed sites and a preponderance of quite dense stands (basal area averaged 149 square feet per acre in pine and Gambel oak). The models imply that nonherbage variables are relatively unimportant and that the key to high scenic beauty is to plant grasses and forbs and restrict grazing. However, while such efforts would certainly contribute to higher scenic beauty, the practical relationship between herbage and overstory must not be ignored. Beyond direct range management actions such as fertilizing and planting grass and forbs or restricting grazing, herbage can only be increased by removing overstory.

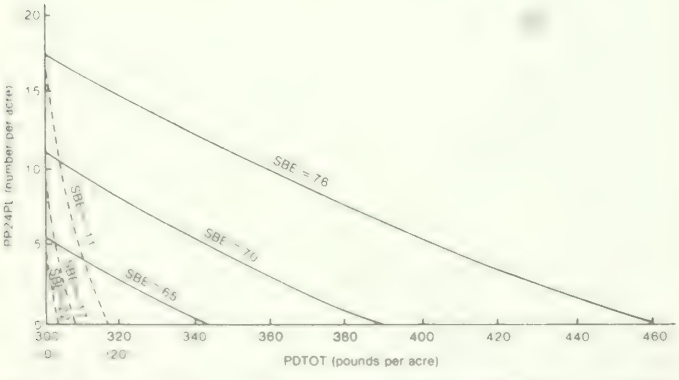


Figure 6.—Isoquants of mature ponderosa pine (PP24PL) and herbage (PDTOT) given fixed quantities of smaller pine and downed wood, preharvest basic model.

A related apparent implication of these two models is that additional large ponderosa pine and herbage can compensate for the deleterious effect of smaller pine trees and downed wood on scenic beauty. However, in practice, increasing amounts of positive variables can not be continually added to compensate for increasing amounts of the negative variables. In general, increasing numbers of immature pine trees reduces herbage quantity and, at higher stand densities, can only be obtained at the cost of fewer mature trees. The limitations of static, linear models such as these must be recognized.

While overstory and understory are unavoidably linked, downed wood quantity is independently under the control of managers. When downed wood is characterized only by total volume, as in the basic model, only small changes in SBE can be caused by manipulating downed wood quantities. Again within the bounds of the original data, the basic model suggests that a change of only 24 SBE units could be caused by removing all downed wood from the most heavily burdened site. However, when downed wood is characterized, as in the detailed downed wood model, by two separate size classes (DWV014 and DWV3PL), the maximum improvement in scenic beauty is 59 SBE units, 36 attributed to the removal of the small diameter downed wood and 23 attributed to the removal of downed wood 3 inches in diameter and greater.

In addition to the models presented, stepwise solutions given other groups of available independent variables also were obtained. Some of these groups of variables contained the variables of the basic model, plus sets of variables that showed some promise of accounting for variance in scenic beauty in bivariate comparisons. However, addition of these variables produced only moderate improvements in model R^2 and significance. For example, when percentage of ground cover (eight categories), number of stumps (four size classes), percentage of mechanical disturbance, and number of brush piles were available along with the basic variables, seven independent variables were included (PP516, PP24PL, PDTOT, three ground cover variables, and number of brush piles) in an equation accounting for 51 percent of the variance in SBE. And, when the eight summary variables (available to the summary variable model described above), number of Gambel oak larger than 5 inches d.b.h., fuel depth, percentage of downed wood in slash, number of brush piles, and percentage of mechanical disturbance also were available, 10 independent variables were included (PP516, PP24PL, PDTOT, PDTOT75, DWVTOT, TG, ASPECT, site index, number of oak, and number of brush piles) in an equation accounting for 55% of the

variance in SBE. Thus, the availability of additional variables improved model R^2 by at most 6 points (from 0.49 to 0.55). This modest improvement perhaps would not justify the effort required to obtain measurements of the additional variables.

A stepwise solution also was obtained for a set of independent variables identical to those available to the basic model, except that herbage canopy and height were substituted for herbage weight. The resulting equation included six independent variables (PP516, PP24PL, herbage canopy and height, and nonlinear terms for herbage canopy and height) and accounted for 54% of the variance in SBE. Thus, substitution of more visually descriptive measures of herbage for the weight measure improved R^2 by 5 points, even without a downed wood variable. Because herbage canopy and height measurements are less costly than weight measurements (the former do not require clipping and weighing of herbage to adjust for moisture content), the substitution is perhaps warranted for future scenic beauty modeling efforts. Finally, when numerous additional variables were available, an herbage canopy and height model of nine variables accounted for 60% of the variance in SBE.

Postharvest Site-Level Model

Postharvest models were developed from data collected at sites in stands that had recently been harvested. Most of the 120 sites used in the stepwise regressions contained harvest effects. Some of the 1980 slides contained scattered slash and some of the 1981 slides contained piled slash. Most postharvest slides showed considerable mechanical ground disturbance.

Variable sets containing detailed measures of downed wood yielded the most promising models. The following model resulted from availability of the same variable set as that which yielded the preharvest detailed downed wood model:

$$SBE = 46.84 - 0.0243\ PPSAP + 0.0652\ PDTOT - 1.8871\ DWV014 - 0.6448\ PCTSL. \quad [4]$$

Herbage weight contributes to scenic beauty, while pine saplings, small diameter downed wood, and percent of downed wood as slash (PCTSL) detract from scenic beauty. Scenic beauty in this model is much more sensitive to changes in downed wood than to changes in overstory and herbage quantities. The model accounts for only 41% of the variance in SBE (table 2). Apparently, the physical variables measured are not as useful in predicting scenic beauty for postharvest scenes as they are for the less complex preharvest scenes.

Limitations of Site-Level Models

Stepwise models, requiring an F-level of 4.0 for an individual variable to be included, accounted for at most 60% and 48% of the variance in SBE for the preharvest and postharvest sites, respectively. The variance in SBE not accounted for by these models probably can be attributed to numerous factors, aside from omitted forest- and range-related physical variables and data collection and manipulation errors.

First, physical, mensurational variables may not fully explain responses about scenic beauty, which incorporate human perception and judgment. Many landscape assessment techniques rely totally on design variables such as color, texture, form, and variety. Arthur (1977) showed that most of the variance in SBE can be accounted for by estimates of design variables for slides shown in a setting similar to that used for this study. In

Table 2.—Postharvest site-level detailed downed wood scenic beauty model.[a]

Terms in the equation							Model[b]	
				Range				
Description	Name	Mean	SD[c]	Min	Max	R^d with SBE	Coef	Beta
Number of pine saplings	PPSAP	114.2	228.7	0	1300	−0.19	−0.0243	−0.18
Total herbage weight (lb/acre)	PDTOT	135.1	104.9	1	795	0.23	0.0652	0.20
Volume of small diameter downed wood	DWV014	7.5	4.8	1	29	−0.27	−1.8871	−0.29
Downed wood percent slash	PCTSL	54.5	25.4	0	100	−0.47	−0.6448	−0.57
Constant							46.84	
Model summary statistics								
R^2							0.41	
Adjusted R^2							0.39	
F-level[e]							20.91	
Standard error							24.50	

[a] *Based on 120 cases.*
[b] *All variables have an F-level ≥ 4.0 and are significant at the 0.05 level.*
[c] *Standard deviation.*
[d] *Pearson's correlation coefficient.*
[e] *Model significant at the 0.001 probability level.*

addition, this study did not include other variables measurable on-site, such as lighting or sky characteristics.

Second, field measurement of the physical characteristics did not perfectly describe those characteristics. On the one hand, physical variables were only sampled at the inventory points (fig. 2). For example, trees of at least 5 inches d.b.h. were tallied using a 10-factor prism, herbage was sampled in eight 9.6 square foot plots per site, and downed wood was sampled along eight 40-foot transects per site. On the other hand, a mismatch occurred between what the four photographs per site recorded, and how the physical variables were measured. For example, trees were sampled for the full 360° around the inventory center point, while the four photographs taken at the point encompassed only 128°. Also, the depth of view in the photographs did not always correspond well with the location of the physical measurements. At very densely treed sites, some physical features were measured beyond the photographic depth of view, while at sparse sites, considerable areas of the forest seen in the photographs were beyond the distance of the physical measurements.

Third, the equation form used may be less than the best-fit form. Fourth, the photographic quality of the slides differed. Finally, scenic beauty judgments of the slides may be subject to order effects and person-to-person (and group-to-group) differences that are not adjusted for in the SBE scaling procedure.

Stand-Level Models

Aggregating site-level data to the timber stand level alleviated some of the sampling problems associated with site-level models. The site-level estimates in each preharvest stand were averaged to yield 23 stand-level cases. In addition, the averages for the ordinal variables (e.g., TG) were rounded to the nearest whole number to maintain the nominal characteristics of those variables. Stand average SBE ranged from −32 to 64, and averaged 16 with a standard deviation of 25.

A stepwise solution given the basic variables (PPSAP, PP516, PP1624, PP24PL, PDTOT, DWVTOT), plus nonlinear terms for these variables, resulted in a model of two terms (PP24PL and PDTOT) accounting for 70% of the variance in SBE (table 3):

$$SBE = -32.47 + 4.6999\ PP24PL + 0.3806\ PDTOT. \quad [5]$$

The standard error of the estimate for this model is only 14, or about one-half as large as for the comparable point-level model (table 1). However, the range in SBE for the stand-level data is only 47% of that for the site-level data.

Stepwise solution with detailed downed wood variables substituted for DWVTOT in the above variable set yields a model of three terms that accounts for 80% of the variance in SBE (table 3):

$$SBE = 4.35 + 3.6079\ PP24PL + 0.2788\ PDTOT - 2.2606\ DWV014. \quad [6]$$

Both this and the basic stand-level model are highly significant, and account for much more of the variance in SBE than do the site-level models.

A third stand-level model, resulting from the availability of only overstory variables (trees per acre by size class plus summary variables) yielded a model of two terms accounting for 55% of the variance in SBE (table 3):

$$SBE = -41.17 + 5.5076\ PP24PL + 22.5761\ TG. \quad [7]$$

Table 3.—Preharvest stand-level scenic beauty models.[a]

Terms in the equations							Models[b]					
Description	Name	Mean	SD[c]	Range		R^d with	Basic		Detailed downed wood		Overstory	
				Min	Max	SBE	Coef[e]	Beta[f]	Coef	Beta	Coef	Beta
Mature pine (trees/acre)	PP24PL	3.6	1.7	1	8	0.35	4.6999	0.32	3.6079	0.24	5.5076	0.37
Total herbage weight (lb/acre)	PDTOT	82.7	49.4	15	233	0.72	0.3806	0.76	0.2788	0.56		
Small diameter downed wood volume (ft^3/acre)	DWV014	10.8	4.2	5	22	−0.73			−2.2606	−0.38		
Tree grouping	TG	1.7	0.7	1	3	0.64					22.5761	0.65
Constant							32.47		4.35		−41.17	
Model summary statistics												
R^2							0.70		0.80		0.55	
Adjusted R^2							0.67		0.76		0.50	
F-level[e]							23.06		24.81		12.05	
Standard error							14.29		12.02		17.50	

[a] *Based on 23 cases.*
[b] *All variables have an F-level ≥ 4.0 and are significant at the 0.05 probability level.*
[c] *Standard deviation.*
[d] *Pearson's correlation coefficient.*
[e] *All models are significant at the 0.001 probability level.*

At the timber stand level, one can account for much of the variance in scenic beauty of the preharvest Woods/Bar-M stands by knowing only the number of mature ponderosa pine trees per acre and the tree grouping category.

As stated, the data used to build the stand-level models were obtained by averaging site-level data. The site-level SBEs were obtained from judgments of slides that were presented in a random order, rather than being presented in groups by stand. However, tests reported by Boster and Daniel (1972) and Daniel and Boster (1976) showed high correspondence between on-site judgments obtained once the observers had viewed a forest area and the mean of single slide judgments for slides taken in the same area.

Tests of Site-Level Models

The site-level models were tested on the Coconino National Forest and Colorado Front Range data sets used by Schroeder and Daniel (1981). Because the Woods Canyon and Bar-M sites were almost entirely free of insect and disease damage and were forested almost entirely with ponderosa pine, only those sites of the Coconino and Colorado data sets without damage and with overstories of at least 90% ponderosa pine were used. In addition, only those points with less than 10% of the downed wood in sound slash were selected, resulting in data subsets of 31 and 29 cases for the Coconino and Colorado areas, respectively.

Both the basic and detailed downed wood preharvest models (table 1) accounted for about 34% of the variance in SBE of the Coconino points. But they performed poorly on the Colorado points, each accounting for only about 10% of the variance in SBE. However, new models, restricted to the variables in the Woods/Bar-M models (Table 1), accounted for about 43% and 40% of the variance in SBE for the Coconino and Colorado areas, respectively. This suggests that while the same variables are rather important in the three areas, their relative weight differs among the areas.

Removing the restriction on the proportion of downed wood that is sound slash increased the Colorado data subset to 60 points. The postharvest detailed downed wood model (table 2) performed poorly on this Colorado data set, accounting for only 10% of variance in SBE (the model could not be used on the Coconino data, because PCTSL was not measured for that study). When the model was free to choose the coefficients, yet restricted to the four variables of the Woods/Bar-M model (Table 2), it accounted for only 17% of the variance in SBE.

In general, the stepwise models derived from the Woods/Bar-M area apply reasonably well to the Coconino ponderosa pine sites, but quite poorly to the Colorado Front Range. Schroeder and Daniel (1981) reported considerably higher R^2s for the models they developed from the Coconino and Colorado data sets than were obtained using the variables of the Woods/Bar-M models. Schroeder and Daniel's (1981) models separate shrubs from grasses and forbs, combine timber sizes differently, and include only the slash portion of downed wood. Furthermore, their Colorado model contains variables representing other overstory species. On the Woods/Bar-M area, large pine (PP24PL) is the most important pine size category for scenic beauty, and shrubs contribute to scenic beauty. On the Colorado Front Range, few pine greater than 24 inches d.b.h. are found, and shrubs detract from scenic beauty.

Nevertheless, while areas differ, these relationships between scenic beauty and physical characteristics hold for all three areas: large pine trees, grasses, and forbs enhance scenic beauty, while downed wood and small trees in sufficient numbers detract from scenic beauty.

INTERPRETATION OF SCENIC BEAUTY ESTIMATES

What does an SBE of -27 mean? How good is an improvement of 19 SBE units? Merely knowing that an area is judged 27 SBE units lower than the base area, or that one management alternative results in scenic beauty being 19 units better than an other alternative, is inadequate. Some way to interpret the magnitude of an SBE is necessary. Two approaches to interpretation are presented here. The first relies on photographs depicting points along the range of scenic beauty. The other utilizes a scenic beauty distribution.

Representative Scenes

The scenic beauty values predicted by the models are statistical estimates of public evaluations of forest landscapes. Each estimate reflects a set of physical characteristics. To help visualize what the scenic beauty values mean, sites representing low, medium, and high scenic beauty have been selected from those used to build the basic preharvest model and the detailed downed wood postharvest model. With each set of representative scenes, the actual SBE and physical feature data at the site where the photos were taken, and the predicted SBE based on these data, are presented. Figures 7, 8, and 9 depict scenes used to build the preharvest scenic beauty models; figures 10, 11, and 12 depict scenes used to build the postharvest scenic beauty model. Note that the high scenic beauty site shown for the postharvest model (fig. 12) contains almost no harvest effects (the upper right photo shows some slash in the background). Although the site is in a harvested stand, the area near the point was essentially undisturbed.

As figures 7 through 12 help depict, high or low levels of scenic beauty may result from different combinations of physical features. For example, low scenic beauty may occur where there are large amounts of visible slash (fig. 10), or in a dense pole stand with some downed wood but no slash (fig. 7). Or, high scenic beauty

Pine saplings (no./acre): 200
PP d.b.h. 5-16 (no./acre): 392
PP d.b.h. ≥24 (no./acre): 12

Herbage (lb/acre): 5
Downed wood (ft^3/acre): 1259

Actual SBE: −53
Predicted (basic preharvest model) SBE: −25

Figure 7.—A preharvest site of low scenic beauty.

SBE = 58

SBE = −31

SBE = 41

SBE = 24

PP saplings (no./acre): 200
PP d.b.h. 5-16 (no./acre): 27
PP d.b.h. ≥24 (no./acre): 7.1

Herbage (lb/acre): 45
Downed wood (ft^3/acre): 1397

Actual SBE: 23
Predicted (basic preharvest model) SBE: 14

Figure 8.—A preharvest site of medium scenic beauty.

A

SBE = 84

B

SBE = 155

C

SBE = 59

D

SBE = 56

PP saplings (no./acre): 150
PP d.b.h. 5-16 (no./acre): 5
PP d.b.h. ≥ 24 (no./acre): 10

Herbage (lb/acre): 380
Downed wood (ft^3/acre): 749

Actual SBE: 89
Predicted (basic preharvest model) SBE: 86

Figure 9.—A preharvest site of high scenic beauty.

SBE = −56

SBE = −24

SBE = −11

SBE = −12

PP saplings (no./acre): 0
Herbage (lb/acre): 44

Downed wood < ¼-inch diameter (ft^3/acre): 8
Percent slash: 95

Actual SBE: −26
Predicted (detailed downed wood postharvest model) SBE: −20

Figure 10.—A postharvest site of low scenic beauty.

A

SBE = 31

B

SBE = 10

C

SBE = 0

D

SBE = 1

PP saplings (no./acre): 0
Herbage (lb/acre): 119

Downed wood < ¼-inch diameter (ft^3/acre): 16
Percent slash: 34

Actual SBE: 11
Predicted (detailed downed wood postharvest model) SBE: 8

Figure 11.—A postharvest site of medium scenic beauty.

A

SBE = 57

B

SBE = 49

C

SBE = 124

D

SBE = 96

PP saplings (no./acre): 0
Herbage (lb/acre): 293

Downed wood < ¼-inch diameter (ft^3/acre): 1
Percent slash: 20

Actual SBE: 82
Predicted (detailed downed wood postharvest model) SBE: 51

(Note: This site was not harvested. However, it is in a stand that was largely harvested, and was included in the postharvest data.)

Figure 12.—A postharvest site of high scenic beauty.

may occur in relatively open areas having large pine trees and moderate herbage amounts (fig. 12), or in areas of medium density having some large pine trees and heavy herbage amounts (fig. 9).

Individual scenes may deviate somewhat from the values predicted for them by the model. This is to be expected, because the predicted value is the expected average for the entire site. For example, the SBEs for the four photos in figure 7 range from −104 to 16. Any site potentially offers a great many individual views, each differing from the average. Some types of forest sites (or stands) may be more variable in this respect than others. Special features, such as occasional meadows or dense "dog hair" thickets, are expecially likely to produce deviations from the average value, especially if they are beyond the range of the physical inventory but captured in the photos.

Scenic Beauty Distribution

Perhaps the best aid to interpretation of SBEs is a distribution of SBEs for some meaningful geographical area. Such a distribution would allow calculation of the percentage of the sites in the overall area that is more, or less, preferred than the one in question. Furthermore, a change in SBE for a site could be interpreted as a change from one percentile to another.

As an example, consider the distribution of scenic beauty for the Woods/Bar-M area. To determine this distribution, the timber stands in the area were delineated and categorized by stand type. Sixteen percent of the 504 delineated stands were selected for inventory based on the distribution of stand types within the overall area, and photographs were taken at 15 sites per stand according to the procedure described above for the modeling data. The SBEs on the 1,204 usable sites range from −84 to 122 and average 18 SBE units. As seen in figure 13, they are approximately normally distributed.

The preharvest Woods/Bar-M scenic beauty distribution in figure 13 is depicted in figure 14 as a cumulative frequency distribution. With figure 14, any specific site or stand SBE can be put in perspective relative to the Woods/Bar-M area. For example, a site of −20 SBE units has higher scenic beauty than only 13% of the Woods/Bar-M area, and an improvement in scenic quality of that site to an SBE of 40 signifies an improvement to the 74th percentile.

The Woods/Bar-M scenic beauty distribution is adequate for illustrative purposes; but, it lacks operational practicality for two reasons. First, the geographical area encompassed by the Woods Canyon and Bar-M Watersheds is small and its vegetation is rather homogeneous. Second, all photographs reflect preharvest conditions, which is unrealistic for timber lands managed under multiple use concepts.

The geographical area included in an operational SBE distribution probably should encompass an important administrative area, such as a national forest. If two or more forests contained similar forest characteristics,

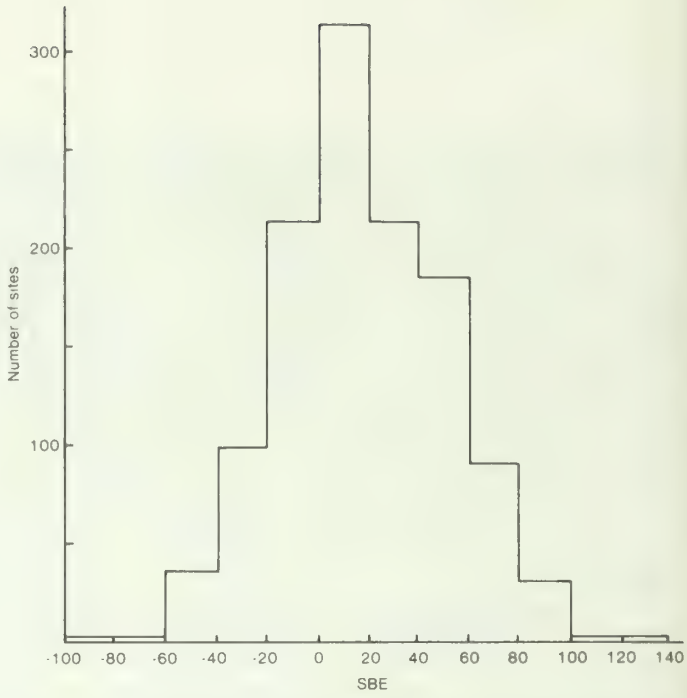


Figure 13.—Distribution of scenic beauty (SBE) for Woods Canyon and Bar-M Watersheds before harvest (based on 1,204 sites with a mean SBE of 18).

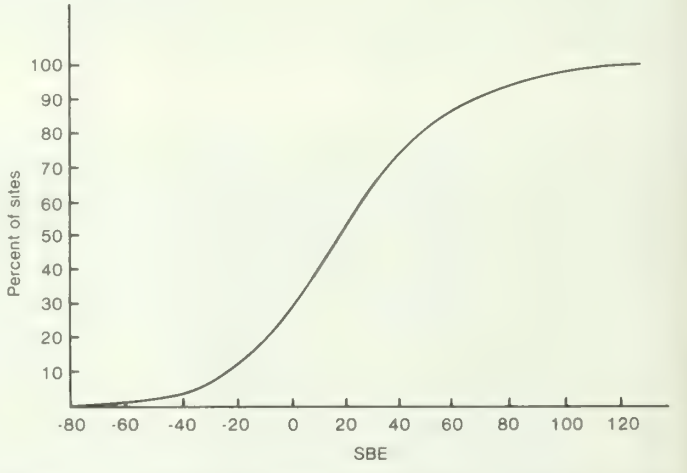


Figure 14.—Cumulative frequency distribution of scenic beauty (SBE) for Woods Canyon and Bar-M Watersheds before harvest.

the SBE distribution could include those forests, thereby reducing overall sampling cost.

The mix of the conditions to be represented in an SBE distribution is largely characterized by the proportion of the slides that contain harvest effects, disease or insect damage, specific stand types, and specific tree species. The most appropriate mix, or set of mixes, to use in building SBE distributions should reflect realistic conditions for usual forest visitors. If visitors are likely to see a proportional cross section of the entire administrative area, then a mix reflecting the distribution of conditions within the entire area is warranted. However, if visitors typically see only a portion of the administrative area, the mix should probably reflect the distribution of conditions in that portion. Or, if one group of visitors general-

ly sees one portion of the area, while another group sees a different portion, perhaps two mixes and associated distributions are warranted. In any case, the slide presentation context used to obtain SBEs for a given mix should reflect the proportion of different conditions in the mix.

Within each mix, a tradeoff between model precision and model generality is encountered. More precise models, accounting for greater portions of the variance in SBE, more often can be obtained if they are built upon subsets of the data reflecting specific overstory species or stand characteristics, than if they are built upon the entire data set for the mix. For example, individual models for preharvest single- and two-storied sites have higher R^2s than the model for both one- and two-storied sites. However, such stratification increases the complexity of the modeling effort and makes use of the models more cumbersome.

USE OF SCENIC BEAUTY MODELS

The scenic beauty models provide many insights into the nature of near-view ponderosa pine scenic beauty that have implications for forest management. Furthermore, they provide new opportunities for enhancing forest landscape assessment procedures.

Forest Management

The coefficients of the models presented here suggest that, for the study area, large pine trees, Gambel oak, and herbage contribute to scenic beauty, while smaller pine trees and downed wood detract from scenic beauty. Furthermore, less dense pine stands of less tree grouping and stands of a northerly aspect are preferred. In addition to these rather general statements, use of the models allows comparison of numerous stand conditions. The implications of the models for questions of stand structure and density, slash treatment, and grazing follow.

Stand Structure and Density

Based on criteria adapted from Meyer's (1938) description of even-aged ponderosa pine stands, 58% of the sites used to build the preharvest models and 66% of the sites used to build the postharvest models were characterized as even-aged. Thus, the models were built with a set of data representing a good mix of even- and uneven-aged sites. Assuming constant herbage and downed wood amounts, the preharvest basic model predicted SBEs for even-aged stands ranging about 30 SBE units from most preferred (mature sawtimber) to least preferred (sapling) stands. Predicted SBE for an all-aged stand fell close to the mid-point of the 30-point range for even-aged stands. Thus, even-aged mature sawtimber stands were preferred to all-aged stands, which, in turn, were preferred to even-aged sapling stands, all else being equal. However, because the standard error of the estimate for the model is about 27 SBE units, this analysis is less than conclusive.

Predicted SBEs of the preharvest basic and detailed downed wood models (table 1) and the postharvest detailed downed wood model (table 2) were compared for six hypothetical ponderosa pine stands. The six stands, which range from 20 to 120 square feet of basal area per acre, are all-aged stands, each containing trees from 1 to 30 inches d.b.h. (table 4). For each stand, the number of trees in any 1-inch diameter class is 1.2 times the number in the next larger 1-inch class. Herbage weight increases as overstory density decreases. The herbage estimates were obtained using an equation developed from data for pine stands on the Coconino National Forest (table 4). These estimates of potential ground cover assume the absence of grazing. Livestock or wildlife grazing would reduce the herbage estimates.

SBEs predicted using each of the three models, for each of the six timber stands, assuming no downed wood, are listed in table 4 and graphed in figure 15. The models predicted very similar estimates of SBE, differing at most by 16 SBE units at 20 square feet of basal area. The preharvest context models show SBE decreasing by more than 40 SBE units as density increases from 20 to 120 square feet of basal area. The postharvest model is less sensitive to this density change, showing a decrease in SBE of 30 units.

The relationship between scenic beauty and stand density depicted in figure 15 shows a clear preference for stands of only 20 square feet of basal area. However, because of the data upon which the models are based, one can not conclude that large areas of such sparse stands are preferable to areas of a mixture of stand densities. First of all, most sparsely treed inventory sites were surrounded by areas of greater density. Because it is easier to see surrounding, untallied, trees when one is in a sparse stand, it is likely that many photographs taken in sparse stands showed denser areas in the distance. More important, all subjects responded to a mixture of slides representing a wide range of stand densities, somewhat similar to the mixture of sites one would see on an actual trip through similar forests. The fact that, in relation to dense sites, sparse sites were preferred does not prove that uniformly sparse forests are preferred to denser forests or forests of mixed density. The importance of spatial distribution of a variety of stand conditions on preferences for forest areas must be understood before the near-view scenic beauty models can be fully and appropriately applied to forest management.

Harvest and Slash Cleanup

The detailed downed wood models are more sensitive than the basic models to downed wood changes. The postharvest model is most appropriate for estimating the initial effect of harvest on scenic beauty, and the preharvest model is more appropriate for estimating the long-run effect.

Consider an all-aged stand of 120 square feet of basal area that could be harvested selectively to various den-

Table 4.—All-aged stands of differing density.

	Basal area (ft^2/acre)					
	20	40	60	80	100	120
Ponderosa pine (trees/acre)[a]						
0.1-4.9 inches d.b.h.	30	59	86	118	149	183
5-15.9 inches d.b.h.	24	48	69	95	119	145
16-23.9 inches d.b.h.	2.9	5.6	8.2	11.4	14.3	17.3
≥24 inches d.b.h.	0.6	1.3	1.8	2.5	3.2	3.8
Herbage (lb/acre)[b]	617	420	313	254	222	204
Predicted SBE						
Preharvest site-level						
Basic model	98	84	72	63	58	54
Detailed downed wood model	102	88	77	69	64	61
Postharvest site-level						
Detailed downed wood model	86	73	65	61	58	56

[a] *Based on a Q-value of 1.2.*
[b] *Based on the following equation:*

$$PDGFS = 18313 + (22.45ANNPRE + 58.52SOIL - 1.36ANNTEMP)\,(e^{-0.0084GSL})^3.$$

The equation form is a modification of Clary (1978). The equaton was calibrated with data for 9,151 plots collected for 20 years on Beaver Creek watershed (H. Brown, et al. 1974) and on Wild Bill Experiment Range (Pearson and Jameson 1967). Average Woods Canyon amounts of 26, 43, and 4.5 were used for ANNPRE (annual precipitation), ANNTEMP (annual average temperature), and SOIL (average soil depth), respectively.

sity levels (table 5). If all slash were removed following harvest, the preharvest and postharvest models would both predict higher scenic beauty at each heavier harvest (fig. 16). Furthermore, the two models yield quite similar predictions, suggesting that short- and long-term scenic beauty would be similar.

However, if some or all of the slash is left on-site, short-term scenic beauty may be greatly affected. As seen in figure 16, the postharvest model shows SBE dropping dramatically with even a moderate harvest if some slash is left. The model is very sensitive to slash percentage (PCTSL) and small diameter downed wood (DWV014). In the example, all downed wood is slash, and much of it is of small diameter, because it consists of only branches and tops of less than 5 inches in diameter (all other wood is assumed to be harvested).

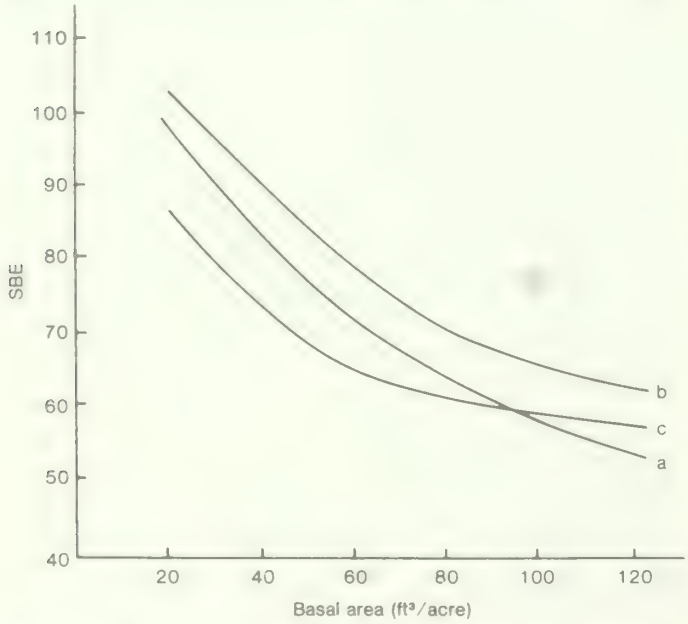


Figure 15.—Change in SBE with basal area for three site-level models: a—preharvest basic model, b—preharvest detailed downed wood model, c—postharvest detailed downed wood model.

In the long run, as predicted by the preharvest model, the effect on SBE of leaving some or all the slash, as was done in the actual harvests on the Woods/Bar-M area more than 30 years ago, is moderately negative.

Unfortunately, as shown by the dotted lines in figure 16, most of the predicted SBEs for the no-slash-removal option, and some of the SBEs for the one-half-slash-removal option, are based on estimates of small diameter downed wood (DWV014) which outstep the bounds of the original data. The recently harvested Woods/Bar-M sites did not include sites of such a drastic harvest level as the heavier harvests considered here.

Grazing

Of the physical variables measured for this study, herbage has by far the largest effect on scenic beauty of preharvest conditions and the greatest positive effect on scenic beauty of either preharvest or postharvest conditions (see, for example, the beta coefficients of tables 1, 2, and 3). This has obvious implications for range management, for (with the exception of any increase in scenic beauty from increases in sightings of grazing animals) scenic beauty and grazed animals are competing products. Furthermore, changes in overstory that benefit scenic beauty may create conflicts with grazing interests. Consider that, for areas of overstory density

Table 5.—Effect of harvest of an all-eged stand of 120 square feet of basal area per acre.

	Basal area (ft^2/acre)								
	120	115	110	105	100	90	80	60	40
Ponderosa pine (trees/acre)									
0.1-4.9 inches d.b.h.	183	175	166	158	149	134	118	86	59
5-15.9 inches d.b.h.	145	139	132	126	119	107	95	69	48
16-23.9 inches d.b.h.	17.3	16.5	15.8	15.1	14.3	12.8	11.4	8.2	5.6
≥24 inches d.b.h.	3.8	3.7	3.5	3.4	3.2	2.9	2.5	1.8	1.3
Herbage (lb/acre)	204	207	211	215	222	235	254	313	420
Downed wood (ft^3/acre)[a]									
Total	0	41	81	122	162	220	277	408	523
< ¼ inch diameter	0	8	15	23	30	34	38	54	61
>3 inch diameter	0	6	12	17	23	34	46	69	85

[a]*Downed wood created with harvest.*

similar to the Woods/Bar-M area before harvest, which averaged 145 square feet of basal area, scenic beauty and herbage for livestock and wildlife can both be increased by harvest of part of the overstory, once the scars of harvest have healed. That is, decreasing overstory density can improve both scenic beauty and grazing potential. However, increases in grazing in response to the increased herbage supply will lower scenic beauty of ponderosa pine areas similar to those of the study area. The grazing/scenic beauty tradeoff thus may be a concern, particularly in areas frequented by recreationists.

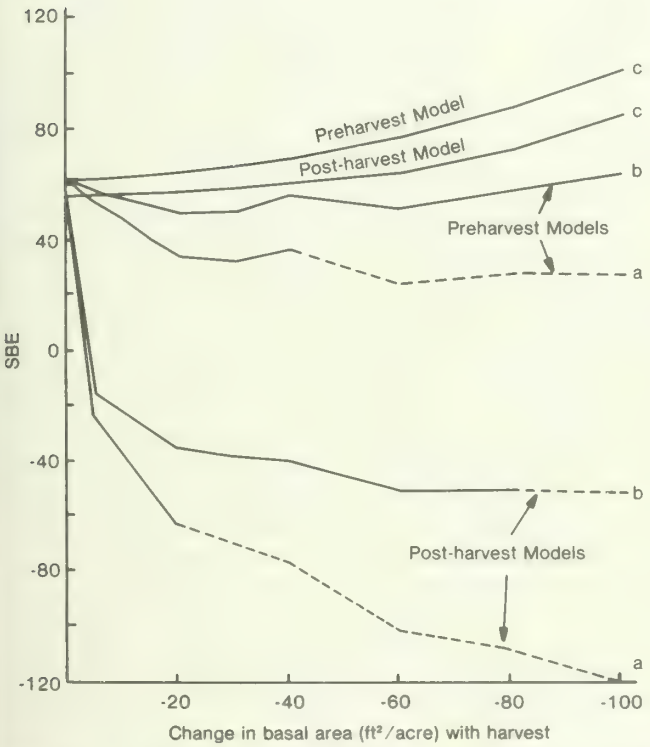


Figure 16.—Change in SBE with harvest of a stand of 120 square feet of basal area as predicted by detailed downed wood site-level models (dotted lines indicate that model is being used outside the range of the original data).

a—no downed wood removal,
b—removal of one-half of downed wood,
c—complete removal of downed wood.

Landscape Assessment

In current national forest management, integration of scenic quality with other resources and concerns is crucial. Therefore, it is, important to consider the potential contribution of scenic beauty modeling efforts to forest scenic quality management capabilities.

Daniel and Boster (1976) listed three potential contributions of quantitative assessments of perceived scenic beauty to forest management:

1. Better integration with other resources and products.
2. Better justification for land-use decisions.
3. Restoration of the client-architect relationship.

Integration

"Integration" may once have involved largely informal processes, where managers or planning teams attempted intuitively to balance the mixture of forest effects and products. Increasingly, however, this process has become more formal and systematic. Quantitative models project management-induced changes in forest characteristics with considerable precision, and complex linear programs are employed to allocate management resources so as to achieve multiple-use goals efficiently. Integration of scenic resources in this context can be greatly facilitated by the quantitative precision of psychophysical assessments of forest scenic quality and by the explicit relationships between scenic beauty and other measurable, manageable features of the forest provided by the scenic beauty models. Scenic beauty models make it possible to project the scenic consequences of management actions with specified levels of accuracy. Thus, tradeoffs between scenic and other objectives can be evaluated and negotiated with greater precision and confidence. For example, the impact on scenic beauty of typical overstory management can be assessed, facilitating quantification of tradeoffs between net return from marketed products, such as stumpage, and relative scenic beauty. Furthermore, treatments can be designed to maximize scenic beauty in high-use areas, given the existing stand characteristics.

Justification

Justification of management actions generally involves two major components, a traceable objective decision-making process, and documented evidence of public participation. The scenic beauty estimation method makes the assessment process explicit and objective. The procedures are standard, and the outcome does not depend on the judgment or biases of the individual applying the method. Further, projections of the expected scenic consequences of management alternatives are made with explicit models and with specified levels of reliability.

The public participation requirement is met directly when public perceptual judgments are used to assess scenic quality. While most research has found a high degree of consensus in scenic preferences across many segments of the public, it is possible, and may be advisable in some situations, to make separate assessments for important groups that are suspected to have divergent perceptions of forest scenic quality. By using scenic beauty prediction models to project scenic impacts, public judgments are indirectly used to evaluate management alternatives. Thus, public participation is provided at several levels of landscape management.

Client-Architect Relationship

The client-architect relationship is an important element of most architect's work. Reliance on individual, and perhaps idiosyncratic, judgments can be advantageous for landscape designers working for individual private clients. The intensive interaction between the skilled and sensitive designer and an individual client provides an opportunity for the emergence of a highly creative design that uniquely meets the client's needs and wishes. The forest landscape architect, however, designs for a large and somewhat diverse public. There is little opportunity for intensive interaction. The public client does not have the privilege of selecting a designer with a specific style and approach, and the public does not respond to and influence, on a direct and regular basis, the products of the various stages of design development. Thus, some essential elements of an effective client-architect relationship are not available to the public landscape designer. The scenic beauty models can help to restore the client interaction for the forest landscape architect. They provide explicit input about public preferences.

Scenic Beauty Models and the Visual Management System

The Visual Management System (VMS) was developed and implemented on all national forests to guide and assist landscape architects in scenic quality management. The VMS provides an explicit, standardized procedure based on widely accepted design principles and intuitively reasonable assumptions about viewer sensitivity to scenic beauty and scenic impacts.

Scenic beauty models, such as those presented here, also can be useful tools for the landscape architect. The models complement the VMS system in several ways. First, they provide easily used, quantitative tools that express scenic beauty in terms of other forest resources. Use of scenic beauty models can be facilitated by programming them in hand-held calculators, or providing them as interactive computer programs. Their use should help the landscape architect to function as a full partner in the multidisciplinary team. Integration of scenic resources with other forest products and management concerns is difficult using only the VMS because of the categorical nature of Visual Quality Objectives and the abstract nature of the VMS characterization of the landscape (Daniel and Vining 1983). For example, it is not possible to determine tradeoffs between Visual Quality Objectives and timber volume production except in very gross terms. The relationship between specific harvest-related changes in forest characteristics (e.g., changes in stand density and size distributions or slash accumulations) and formal esthetic features (e.g., variety) is not explicit. Also, the VMS categories often combine large areas that differ in terms of manageable stand characteristics. The scenic beauty models could help provide the degree of quantitative precision at the near-view level necessary to adequately evaluate important tradeoffs.

Second, the scenic beauty models can enhance the landscape architect's credibility among other land management professionals and provide additional justification for the architect's suggestions. Feimer et al. (1981) found very low agreement between individual landscape architects in their judgments of scenic quality and of scenic impacts of various changes in the landscape. Further, judgments of VMS-type landscape features (color, line, texture, etc.) showed inconsistent relationships to global judgments of scenic quality. Because the scenic beauty models rely on public preference, they can supplement the VMS system.

Third, the scenic beauty models can clearly augment the client-architect relationship. The VMS approach alone provides for no direct client-architect interaction. The scenic beauty models provide an easily accessed source of client input that the architect can use in reaching Visual Quality Objectives.

While the scenic beauty models help to quantify scenic beauty, they do not usurp the landscape architect's design perogative, for they do not prescribe any particular forest treatments. As the models show, a given level of scenic beauty can be achieved with numerous combinations of physical characteristics. Many different combinations of large and small trees, downed wood, and vegetative ground cover will all produce the same SBE in ponderosa pine forests. For any particular combination of features, however, a unique SBE value will be determined—a value that is a reliable estimate of a broad cross section of the publics' perception of the scenic quality of the forest.

As the landscape architect works with principles of design and translates them into changes in the visual ap-

pearance of the forest landscape by manipulating biological features, SBE models can be used to provide essential feedback regarding the expected perceptions of the public. That is, the models serve as a surrogate for the public client, providing one source of interaction between public client and forest landscape architect throughout the design process. The landscape architect, combining the features of the VMS and scenic beauty models, and consulting with other resource professionals, could design the combination of landscape features that best meets the needs of the clientele.

SUMMARY AND CONCLUSIONS

The scenic beauty models show that, for the Woods/Bar-M area, observers' verbal judgments of relative scenic beauty of near-view forest scenes can largely be explained in terms of physical characteristics measured on-site using widely accepted forest inventory procedures. Among sites that showed no signs of recent harvest, up to 60% of the variance in perceived scenic beauty can be explained by field measurements of physical characteristics. When site-level data are aggregated to the timber stand level, the variance accounted for is more than 80%. For recently harvested sites, the amount of the variance in perceived scenic beauty explained by site-level measures of physical characteristics drops to at most 50%.

In the Woods/Bar-M area, of all the physical characteristics, herbage had by far the greatest effect on preharvest scenic beauty. The most visually important measure of herbage, combined herbage canopy of grasses, forbs, and shrubs, accounted for 48% of the variance in scenic beauty of preharvest sites and for 79% in preharvest stands. Large ponderosa pine trees and Gambel oak of all sizes also enhanced scenic beauty. Downed wood consistently lowered scenic beauty, especially as slash. In addition, pine saplings and poles detracted from scenic beauty when they were present in large quantities.

The basic stand table, herbage weight, and total downed wood volume variables used in previous studies proved to be the most important for predicting preharvest site-level SBE, accounting for 49% of the variance in SBE. The greatest improvements, over the basic variables, occurred when volume of very fine downed wood, aspect, and a measure of the degree of tree grouping were additionally available, and when herbage canopy and height were available in place of herbage weight. The most effective combination of variables increased the percentage of the variance accounted for by about 10 points above that possible with the basic variables only. The basic variables were of limited utility in predicting SBE for recent postharvest sites; but, when very fine downed wood volume and percentage of the small downed wood in slash were additionally available, prediction improved considerably.

Stand-level models accounted for up to 87% of the variance in preharvest scenic beauty, considerably more than comparable site-level models. The increase in model precision caused by averaging values for the sites within a stand is attributable to a reduction in variability in the data, which, in part, results from amelioration of the problems with the site sampling procedure. The stand models are very promising, because they account for much of the variance in scenic beauty with so few independent variables. A model of only two independent variables (number of large ponderosa pine and herbage weight) explained 70% of the variance in preharvest stand scenic beauty. While such a model, because it includes so few variables, does not allow some of the finer distinctions between sites that can be made with site-level models, the stand-level models should be well suited to decision making at the timber stand level. Testing of these models on another data base, however, would be very important before they were used outside of the study area.

Often downed wood and herbage estimates are not available, and predictions have to be made on overstory data alone. Site-level models do not show great promise here, explaining at most only 30% of the variance in perceived scenic beauty. However, the preharvest stand-level overstory model accounted for 55%, lending additional support to further development of stand-level models.

Respondents generally preferred less dense, less horizontally complex pine stands. Less dense stands generally have more herbage and fewer small- and intermediate-sized trees than denser stands. Less horizontally complex stands are characterized by stands with less tree clumping. Respondents, however, had no clear preferences regarding vertical diversity (number of tree stories) and preferred mature even-aged stands over all-aged stands, but all-aged stands over young even-aged stands. Comparison of the preharvest and postharvest models suggests that moderate harvest of the Woods/Bar-M area would improve scenic beauty once the stand has recovered from obvious harvest effects and that the recovery period can be greatly reduced with slash cleanup.

An important aspect of the context in which the respondents provided their scenic beauty judgments is the mix of overstory densities in the slides. The slide presentation context contained a clear majority of rather dense sites. The observers' preference for less dense sites of more herbage and large trees may not hold in a context of many sparse and few dense sites. The importance of the mix of conditions depicted in the slides must be understood before the results presented here can be applied to estimate the effect of other than marginal changes in conditions similar to those at Woods/Bar-M.

Selected models developed from the Woods/Bar-M site-level data were tested on data representing ponderosa pine sites throughout the Coconino National Forest and on data representing the Colorado Front Range. The models generally did not perform as well for these areas as they did for the Woods/Bar-M area, both because the contexts of the slide presentations for the other areas differed from that of the Woods/Bar-M slides and because of physical differences between the areas. Calibration of the Woods/Bar-M models increased predictability somewhat. Predictability could be further improved by

changes among the models' independent variables, principally separating shrub weight from grass and forb weight and including a variable for intermediate-sized pine sawtimber.

The direction of the effect on perceived scenic beauty of most physical characteristics that are measurable on-site appears to be stable regardless of the mix of physical features of the site or the context of the scenes viewed by respondents. Regardless of the area or context, large pine trees, grasses, and forbs enhance scenic beauty, while downed wood and small pine trees in sufficient quantities detract from scenic beauty. However, the relative contribution of any variable to scenic beauty appears to vary among forests and depends, even within relatively small areas, on the mix of conditions depicted in the scenes viewed.

A general model, complete with coefficients, for all southwestern ponderosa pine probably would be inadequate for most areas. However, it seems reasonable to suggest that the following physical variables should be included in a model to be calibrated for individual, relatively damage free pine sites: numbers of ponderosa pine saplings, pulp and small sawtimber, intermediate sawtimber, and mature sawtimber; weight, canopy, and/or height of grasses plus forbs and of shrubs, plus nonlinear terms of these variables; volume or weight of downed wood in diameter size classes of less than ¼-inch and greater than ¼-inch; tree grouping; and aspect.

Preharvest models reflect stand conditions after the scars of selection harvest have largely healed, while the postharvest model reflects very short-term postharvest stand conditions, with slash and other harvest effects quite obvious at harvested sites. An operational model probably should reflect not just these two situations, but the full range of nonharvest and harvest recovery conditions in proportion to those likely to be encountered by forest visitors.

This study suggests that people's scenic beauty judgments are consistent and intuitively logical. It also supports the psychophysical approach to understanding esthetic preference for near-view forest scenes. Not only can the psychophysical model be used to explain a large percentage of the variance in perceived scenic beauty, but that percentage drops, as would be expected, when scenes become more complex and correspondingly more difficult to characterize with physical variables measured on-site. However, because the southwestern ponderosa pine ecosystem is relatively simple in terms of species diversity and seasonal color changes, and because the topography of the Woods/Bar-M area is relatively flat, the modeling success reported here may be exceptional. The psychophysical approach for modeling scenic beauty must be tested in other ecosystems and topographical situations in order to determine its forest-wide applicability.

The scenic beauty models are well suited to use in forest planning. They could be easily linked to physical simulation models, allowing prediction of near-view scenic effects along with more traditionally quantified forest characteristics. The models allow calculation of the change in scenic beauty with harvest, grazing, and slash cleanup, and suggest that moderate harvest can improve scenic beauty if slash is cleaned up, that grazing can reduce scenic beauty, and that slash cleanup dramatically increases scenic beauty. The models should complement use of the Visual Management System and enhance the landscape architect's ability to manage scenic resources.

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APPENDIX

BIVARIATE RELATIONSHIPS AMONG THE VARIABLES

The independent variables of this study are of a biological or physical nature. All were measured on-site using generally accepted forest and rangeland inventory procedures. In all, 82 physical variables, which fall into seven groups, were considered: (1) 4 land variables (e.g., slope); (2) 7 overstory summary variables (e.g., ponderosa pine basal area per acre); (3) 23 variables listing numbers of trees per acre by species and size class; (4) 10 variables listing grass, forb, and shrub weight, canopy, or height; (5) 9 describing percent ground cover; (6) 4 listing number of stumps per acre by size class; and (7) 25 describing downed wood volume by size and condition class plus downed wood depth, dispersion, and percent slash (see Brown (1983) for a complete description of all 82 variables). This appendix presents more detailed information about relationships among these variables. All measures describe site-level data.

Linear Relationships

Relationships between the variables for site-level data are described based on Pearson correlations significant at the 5% probability level. These correlations indicate the strength of the linear relationship between pairs of variables. The more closely a two-dimensional plot of the site-level values for any two variables fits a straight line, the closer the absolute value of the correlation coefficient is to 1.0.

Land Variables

The inventoried Woods/Bar-M sites range up to a 40% slope. Site index (Minor 1964) ranges from 64 to 89 and averages 78. Increases in both slope and site index were associated with decreasing scenic beauty. Slope and site index were positively intercorrelated, and were positively correlated with the following features, which were all associated with decreasing scenic beauty: number of ponderosa pine in the pulp (5 to 12 inches d.b.h.), small sawtimber (12 to 16 inches d.b.h.), and intermediate sawtimber (16 to 24 inches d.b.h.) size classes, pine basal area, overstory crown canopy, and small diameter downed wood. In addition, slope and site index were negatively correlated with number of large (greater than 24 inches d.b.h.) ponderosa pine, which was positively correlated with scenic beauty (perhaps past harvests of large diameter pine on the better sites contributed to this situation). In other words, more rapid tree height growth was generally found on steeper slopes where stands were denser because of an abundance of pulp- and small and intermediate sawtimber-sized trees. These stands tended to have more small diameter downed wood, fewer large pine trees, and lower scenic beauty.

Movement from a south to north aspect was associated with increasing scenic beauty as well as increases in herbage weight, canopy, and height and with decreases in numbered pine of the pulp to intermediate sawtimber sizes, pine basal area, crown canopy, and volume of small diameter downed wood.

Overstory Summary Variables

Preharvest sites ranged from 20 to 320 square feet per acre of pine basal area, from 260 to 8,800 cubic feet of pine per acre, and from 2% to 98% overstory crown canopy. Basal area averaged 125 and 19 square feet per acre in pine and Gambel oak, respectively. For preharvest sites, increases in scenic beauty were associated with increases in Gambel oak basal area, and with decreases in pine basal area, cubic feet of timber, overstory crown canopy, and degree of tree grouping. Pine basal area, crown canopy, and tree grouping were all positively correlated with number of pine in the pulp, small sawtimber, and intermediate sawtimber size classes, and with volume of small diameter downed wood, and were negatively correlated with herbage amounts and heights and with number of large pine trees. In general, as Rutherford and Shafer (1969) and Daniel and Boster (1976) found, less dense sites had less tree grouping, more herbage, and higher scenic beauty. The increase in scenic beauty as pine basal area decreased was probably enhanced by the corresponding increase in visibility of herbage, mature pine, and oak.

Pine basal area of postharvest sites ranged from 5 to 183 square feet per acre, while timber volume ranged from 140 to 3,000 cubic feet. The strong correlations between scenic beauty and overstory summary variables found for preharvest sites generally were absent for the postharvest sites. Only oak basal area was clearly, positively, associated with scenic beauty among the postharvest sites. The lack of a strong negative correlation between scenic beauty and variables describing pine stand density and grouping probably reflects the generally lower stand densities of the postharvest sites, and perhaps the more obvious harvest effects at some of the least dense sites.

Twenty-nine percent of the preharvest sites had less than 100 square feet of total basal area, 51% had from 100 to 200 square feet of basal area, and the remaining 20% had more than 200 square feet of basal area. The denser sites generally had more pulp- and immature sawtimber-sized pine trees, fewer large pine, less herbage, and lower SBE (table A-1). Increasing ponderosa pine stand density was negatively associated with scenic beauty for all three subsets. The simple correlation between SBE and pine basal area was -0.17, -0.32, and -0.37 for the three subsets in order of increasing total basal area.

Table A1.—Means for selected variables for subsets of the preharvest sites based on total basal area, number of tree stories, and tree grouping.

Variable	Total basal area[a]			Tree stories[b]				Tree grouping[c]			
	<100 (96)[d]	100-200 (171)	>200 (66)	1 (29)	2 (103)	3 (162)	4 (39)	1 (79)	2 (159)	3 (51)	4 (44)
SBE	28	15	2	33	15	12	24	1	10	27	53
Ponderosa pine (trees/acre) Saplings	115	230	142	59	111	233	226	239	214	84	55
5-15.9 inches d.b.h.	56	162	343	165	180	177	99	246	158	138	94
16-23.9 inches d.b.h.	7	13	18	10	13	12	15	13	12	11	12
>24 inches d.b.h.	4.6	3.5	2.1	3.4	2.4	3.8	5.4	2.8	3.6	4.1	3.9
Herbage weight (lb/acre)	98	93	52	100	85	85	87	54	76	113	154
Downed wood (ft^3/acre)	1005	1399	1359	1004	1390	1299	1094	1346	1310	1300	1007
Basal area (ft^3/acre)											
Pine	64	123	218	122	134	125	101	158	121	114	92
Oak	8	19	32	24	20	19	13	22	16	14	30
Total	73	144	251	146	155	145	114	181	137	130	123
Tree grouping[c]	2.4	2.2	1.7	2.7	2.5	2.0	2.0	1.0	2.0	3.0	4.0
Tree stories[b]	2.7	2.7	2.4	1.0	2.0	3.0	4.0	2.6	2.9	2.4	2.0
Crown canopy (percent)	42	59	73	56	62	56	49	65	54	56	54
Site index	75	78	82	78	79	79	75	81	77	76	78

[a] *Square feet per acre.*
[b] *1 = one, 2 = one but some two, 3 = two but some three, 4 = generally three.*
[c] *1 = trees in groups with many interlocking crowns, 2 = some tree trouping but little interlocking of crowns, 3 = very little grouping, 4 = no tree grouping—trees evenly spaced.*
[d] *Number of cases in parentheses. The sum of the cases for each of the 3 groups is 333.*

Each inventory site was categorized on-site into one of four tree story classes: (1) one-storied; (2) generally one-storied, but partially two-storied; (3) generally two-storied, but partially three-storied; and (4) generally three-storied. Of the 333 preharvest sites, 9%, 31%, 49%, and 12%, respectively, were assigned to the four classes. Note that sites assigned to each class may contain cases representing a variety of age classes. For example, single-storied stands of any age class may be included in the first class. The four data subsets are not easily distinguished in terms of most measured variables. For example, total basal area ranges from 114 square feet per acre for tree story class 4 to 155 for class 2 (table A-1). The range from 12 SBE units for class 3 to 33 SBE units for class 1 is small; therefore, firm conclusions about the preference for one class above another are risky.

Sites were also categorized during field inspection into four tree grouping classes: (1) trees in groups with many interlocking crowns; (2) some tree grouping, but little interlocking of crowns; (3) very little tree grouping; and (4) no tree grouping—trees evenly spaced. Twenty-four percent, 48%, 15%, and 13% of the preharvest sites were assigned to the four tree grouping classes, respectively (table A-1). Note that sites assigned to each class may contain sites representing a variety of tree story and age classes. In contrast to the tree story distinction, the four data subsets are distinct in terms of several measured variables. An increase in grouping is associated with increasing stand basal area, increasing numbers of pine saplings, pulp, and small sawtimber trees, and decreasing herbage (table A-1). Thus, increased grouping is generally more common in denser stands crowded with smaller trees. In concert with these characteristics of increased tree grouping, scenic beauty (SBE) decreases as grouping increases. Mean SBE drops from 53 for the sites of no grouping to 1 for the sites of trees in groups with many interlocking crowns (table A-1).

Trees

The preharvest sites averaged 180 pine saplings and 184 larger pine trees per acre, plus 36 Gambel oak saplings and 24 larger oak trees per acre. Increasing numbers of pine trees up to 20 inches d.b.h. for preharvest sites, and of up to 16 inches d.b.h. for postharvest sites, were associated with decreasing scenic beauty. However, because nearly all sites had some pine trees in these size ranges present, it cannot be concluded that the complete lack of such pine trees is preferable to a small number of such trees. Furthermore, increasing numbers of oak and large pine trees were associated with increasing scenic beauty. These findings reinforce those of Klukas and Duncan (1967) about the preference for mature pine stands with clear understory, the conclusions of Arthur (1977), Brush (1979), and Schroeder and Daniel (1981) about the preference for large trees and negative effect of increasing numbers of small trees, and the finding of Schroeder and Daniel (1981) about the positive correlation between Gambel oak and scenic beauty.

Herbage

Preharvest herbage weight of grasses, forbs, and shrubs, respectively, ranged to 330, 680, and 200 pounds per acre, and averaged 22, 51, and 14 pounds per acre. Total weight averaged 87 pounds per acre, while combined herbage canopy averaged 16% and maximum herbage height averaged 10 inches. Herbage quantities on postharvest sites averaged slightly higher than on the preharvest sites.

All weight, canopy, and height measures of grasses, forbs, and shrubs were strongly, positively correlated with scenic beauty for both contexts, with the exception of low positive correlations between scenic beauty and forb weight and height for the postharvest sites. Correlations of canopy and height variables to SBE were generally somewhat higher than corresponding correlations of weight to SBE. For example, the correlations of herbage weight, herbage canopy, and maximum herbage height to SBE for preharvest sites were 0.58, 0.65, and 0.62, respectively. Herbage amounts were generally lower in the denser timber stands, principally because of competition for light and moisture. Both Arthur (1977) and Schroeder and Daniel (1981) reported positive contributions of herbage weight to scenic beauty.

Ground Cover

Preharvest ground cover averaged 77% litter, 6% downed wood, 10% rock, 3.5% bare soil, and 2.5% herbage. Obvious signs of mechanical ground disturbance covered only 3% of the inventoried area.

Percentage of bare soil and percentage of herbage were positively correlated to scenic beauty, while percentage of litter was negatively correlated to scenic beauty. Percentage of ground cover in herbage was closely related to other herbage measures. However, it is not intuitively obvious why bare soil was positively associated with scenic beauty. Perhaps the answer lies in the fact that percentage of bare soil was positively correlated with grass amount and negatively correlated with number of pulp- and intermediate sawtimber-sized pine, pine basal area, and numerous downed wood variables. Similarly, percentage of litter cover, which is probably not inherently displeasing, was positively correlated with number of pine in the pulp, small sawtimber, and intermediate sawtimber-size classes, pine basal area, crown canopy, and small downed wood.

For postharvest sites, average proportion of bare soil increased to 11%, at the expense of slight reductions in all other categories. Furthermore, about 30% of the inventoried area showed obvious signs of mechanical disturbance. Percentage of ground cover in herbage again was positively correlated with scenic beauty. However, the relationships of percentage of bare soil and litter to scenic beauty were reversed from the preharvest context. The negative correlation of percentage of bare soil to scenic beauty for postharvest sites is probably related to the strong positive relationships of bare soil to mechanical ground disturbance and to the percentage of the small downed wood that is slash, both of which are strongly negatively correlated to scenic beauty. Harvest and slash piling both involve mechanical scraping of the ground and an increase in the amount of exposed soil.

Stumps

Preharvest sites averaged about 30 stumps per acre, while postharvest sites averaged about 42 stumps per acre. The recently created stumps were generally less than 6 inches high, considerably lower than the stumps on preharvest sites. Stumps were negatively but weakly correlated with scenic beauty on preharvest sites. For postharvest sites, stumps were negatively correlated with scenic beauty, which was partially the result of the association of number of stumps with other harvest-related effects, such as increased amounts of downed wood and mechanical disturbance.

Downed Wood

Total downed wood volumes for both preharvest and postharvest sites averaged about 1,200 cubic feet per acre. This happened for two reasons. First, the sites that were inventoried after harvest had less than average downed wood before the harvest. Second, some of the large downed logs that were on-site before harvest were skidded to landings during harvest. Sixteen percent of the small diameter downed wood on preharvest sites was estimated on-site to have originated from harvests, which occurred many years prior to the inventory. For postharvest sites, this rose to close to 60%.

Downed wood volumes of all categories were negatively correlated with scenic beauty for both preharvest and postharvest sites. Percentage of the small downed wood that is slash also was negatively correlated with scenic beauty, especially for the postharvest sites. A measure of the distribution of downed wood was not significantly correlated to scenic beauty; but, number of brush piles were clearly negatively correlated to scenic beauty. These findings corroborate those of Daniel and Boster (1976), Arthur (1977), and Schroeder and Daniel (1981) that increasing downed wood amounts and piling of downed wood detract from scenic beauty.

Nonlinear Relationships Between SBE and Physical Variables

Cohen and Cohen (1975) stated "... it is a fundamental law of psychophysics that constant increases in the size of a physical stimulus are not associated with constant increases in subjective sensation." Fechner suggested that a logarithmic function best measures this relationship (see Guilford 1954), while Stevens (1975) suggested a power function. Buyhoff and Wellman (1980) tested these functions, plus an exponential function, for vista scenes, and found that the log function gave the best fit

for regression of the proportion of visible area of color photographs in specific landscape dimensions on perceived scenic quality.

Alternative functional forms were compared for five variables (pine basal area, herbage weight, herbage canopy, herbage height, and downed wood volume) that exhibited some degree of nonlinear relationship with scenic beauty (SBE) for preharvest sites. The exponential ($SBE = b_0 e^{b1X}$) and power ($SBE = b_0 X^{b1}$) forms gave a poorer fit to the data based on R^2 and F-ratio, for all five variables, than did the linear form (table A-2). However, an improvement in fit, over the linear form, was obtained with the log form ($SBE = b_0 + b_1 \log X$) for four of the five variables. While this suggests that Fechner's claim (Guilford 1954) is superior to Stevens' (1975) for scenic beauty judgments of timber stands, the evidence is weak. The largest increase in R^2 of the log form over the linear form was only from 0.34 to 0.38 for total herbage weight. Buyhoff and Wellman (1980) showed much larger increases for vista scenes.

The quadradic form $SBE = b_0 b_1 + b_2 X^2$ is compared with the other forms in table A-2. Given the nature of the curves, the quadradic form described the relationships about as well as possible. The biggest improvement in R^2 was from 0.42 to 0.48 for herbage canopy. Figure A-1 is similar to the quadradic curves for all herbage variables, but obtains a slightly better fit of the data, because an exponent of 0.75 was used instead of 2.0. It depicts the following relationship of SBE and herbage canopy (CCTOT):

$$SBE = 36.82 - 3.34\ CCTOT + 14.31\ CCTOT^{0.75}.$$

The curve depicted in figure A-1 ends at an SBE of 79 where CCTOT is 81, the maximum value for CCTOT in the data set. The curve eventually peaks at an SBE of 82 where CCTOT is 110.

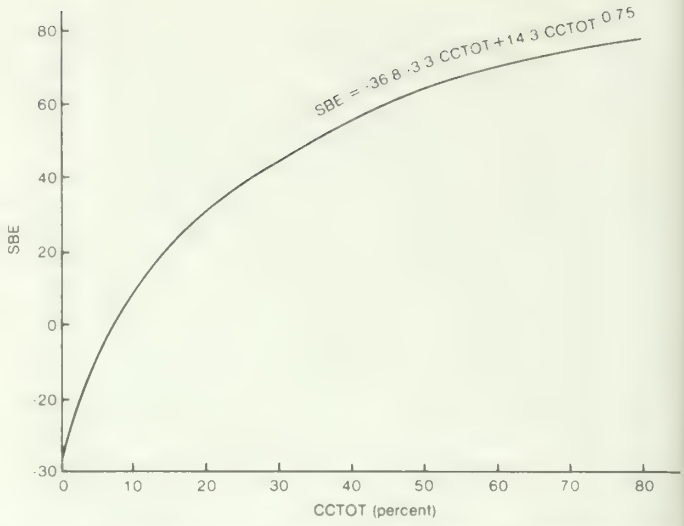

Figure 1A.—Relationship of scenic beauty (SBE) to herbage canopy (CCTOT).

Table A2.—Four functional forms of the relationship between SBE and selected biological variables for 333 preharvest cases.

Variable	Functional form[a]	Equation (SBE =)[b]	R^{2c}	F-ratio
Pine basal area	linear	$42.62 - 0.21X$	0.14	52
	log	$132.60 - 24.81 \log X$	.14	56
	exponential	$22.87\ e^{-0.0083X}$	.09	32
	power	$844.72X^{-0.99}$	.10	35
	quadradic	$51.46 - 0.36X + 0.005X^2$	.14	27
Herbage weight	linear	$-7.63 + 0.29X$	.34	174
	log	$-67.55 + 21.001 \log X$	.38	205
	exponential	$2.81\ e^{0.01X}$	.28	132
	power	$0.2X^{0.93}$	.31	151
	quadradic	$-18.17 + 0.54X - 0.0009X^2$	.39	104
Herbage canopy	linear	$-8.83 + 1.57X$	.42	240
	log	$-38.39 + 23.38 \log X$	.44	262
	exponential	$2.70\ e^{0.07X}$	.34	169
	power	$0.71X^{1.04}$	.37	194
	quadradic	$-21.47 + 3.16X - 0.03C^2$	.48	151
Herbage height	linear	$-19.66 + 3.58X$	.38	202
	log	$-53.99 + 33.31 \log X$	.40	216
	exponential	$1.69\ e^{0.16X}$	.30	143
	power	$0.37X^{1.47}$	.32	157
	quadradic	$-37.19 + 6.73X - 0.10X^2$	.43	123
Total downed wood volume	linear	$27.78 - 90.29X$	.06	22
	log	$72.49 - 8.22 \log X$	.04	13
	exponential	$13.73\ e^{-0.00041X}$	.05	19
	power	$70.73X^{-0.32}$	.02	8
	quadradic	$26.40 - 0.007X + 0.0000005X^2$	.06	11

[a] *Log signifies natural logs.*
[b] *X signifies the independent variable.*
[c] *Coefficient of determination.*

In all cases where a nonlinear functional form provided a better fit than the linear form, the equations indicated a decreasing marginal contribution of the physical stimulus to scenic beauty. Equal increases in pine basal area and downed wood volume were associated with decreasing marginal reductions in scenic beauty; and equal increases in herbage quantities or heights were associated with decreasing marginal increases in scenic beauty.

It is of considerable interest that 48% of the variance in SBE of the preharvest sites can be explained by knowing only the combined canopy of grasses, forbs, and shrubs, and that 43% of said variance can be explained by merely knowing the maximum herbage height (table A-2). When sample point estimates are averaged per stand, providing 23 stand-level cases, these percentages increase to 67% and 79%, respectively. However, while it can be inferred from this that herbage makes an important contribution to preharvest scenic beauty, it can not be concluded that large quantities of herbage are essential to high scenic beauty.

Brown, Thomas C. and Terry C. Daniel. 1984. Modeling forest scenic beauty: Concepts and application to ponderosa pine. USDA Forest Service Research Paper RM-256, 35 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Statistical models are presented which relate near-view scenic beauty of ponderosa pine stands in the Southwest to variables describing physical characteristics. The models suggest that herbage and large ponderosa pine contribute to scenic beauty, while numbers of small and intermediate-sized pine trees and downed wood, especially as slash, detract from scenic beauty. Areas of lower overstory density and less tree clumping were preferred. Moderate harvest of relatively dense stands tends to improve scenic beauty once the stand has recovered from obvious harvest effects. The recovery period can be greatly reduced by slash cleanup.

Keywords: Scenic beauty, landscape assessment, forest esthetics, *Pinus ponderosa*

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Brown, Thomas C. and Terry C. Daniel. 1984. Modeling forest scenic beauty: Concepts and application to ponderosa pine. USDA Forest Service Research Paper RM-256, 35 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

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Experiment Station**

Fort Collins,
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**Research Paper
RM-257**

Warpage of Studs from Young Growth Ponderosa Pine from Northern New Mexico

**Donald C. Markstrom
Craig E. Shuler
Rudy M. King**

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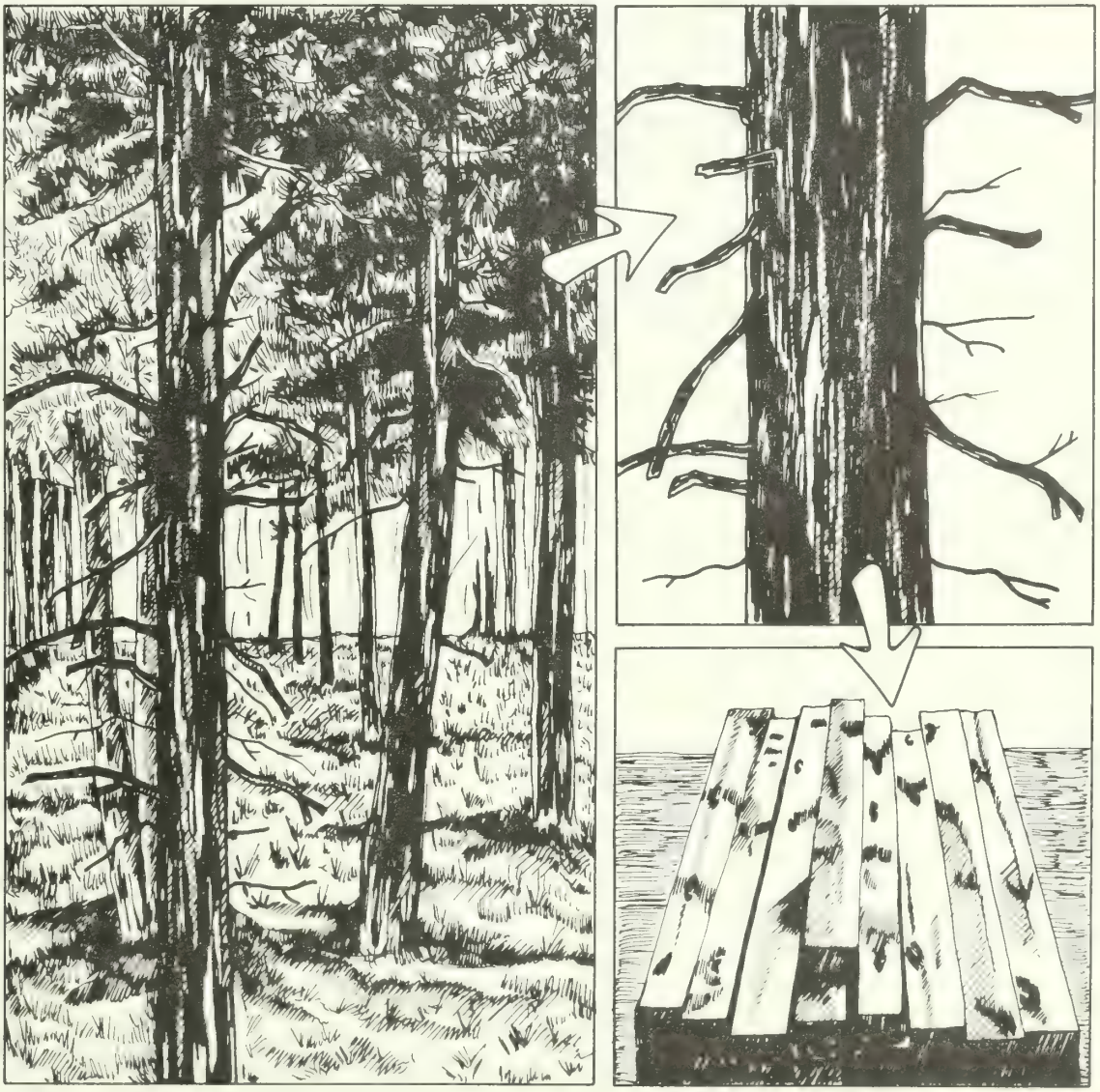

Abstract

Lumber grade recovery and warp of studs from young ponderosa pine trees are affected by tree diameter, but not by a difference in site index from 55 to 100 or log position in the tree. Trees 9 inches d.b.h. yielded lower grade studs with more warp than 10- through 14-inch d.b.h. trees. Logs 5-7 inches d.i.b. yielded lower grade lumber with more warp than 8-12-inch logs after drying to 6% moisture content. Subsequent drying simulating on-site storage indicated that kiln drying to 15% moisture content instead of 19% would not lessen warpage problems. Logs smaller than 8 inches d.i.b. from trees ranging from 9 to 14 inches d.b.h. produced lumber of similar grade and warpage.

SDA Forest Service
esearch Paper RM-257

December 1984

Warpage of Studs from Young Growth Ponderosa Pine from Northern New Mexico

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Warpage of Studs from Young Growth Ponderosa Pine from Northern New Mexico

Donald C. Markstrom, Craig E. Shuler, and Rudy M. King

Management Implications

Much of the dimension lumber from ponderosa pine (*Pinus ponderosa*) in the Rocky Mountains is dried to the industry standard of 19% moisture content, but then is marketed in dry areas where the equilibrium moisture content may be 5% or lower during much of the year. Further drying under these circumstances would increase any tendency for the lumber to warp.

A total of 865 studs were sawn from 82 trees sampled from 9- through 14-inch d.b.h. trees from Northern New Mexico. Analysis of the grade and warpage of the study indicated that:

1. Growing site index did not affect either the grade or the amount of warp.
2. Smaller trees and logs had lower grade recovery and more warp than larger trees and logs.
3. Log position in tree had little effect on grade recovery and warp when log diameter was accounted for.
4. Logs 8 inches or less in diameter, regardless of location in tree, had similar grade and warpage, and were affected only by moisture content.

These research results should help the buyers and sellers to determine the stumpage value of timber.

Introduction

The relationship between drying degrade in lumber from young growth ponderosa pine and size and other characteristics of this class of trees is not well understood. It has been reasoned, with some supporting evidence, that an unusually high incidence of degrade in such timber is caused by juvenile wood and/or compression wood. Both of these characteristics may be more prevalent in young growth ponderosa pine than in mature trees.

Loss of lumber grade from excessive warp usually results from abnormal shrinkage when lumber dries. Longitudinal shrinkage typically ranges from 0.1% to 0.3% when wood is dried from green to ovendry conditions. This shrinkage would be about one-half as much when lumber is dried to 12% moisture content. Longitudinal shrinkage greater than 0.3% from green to ovendry moisture conditions for straight grain material is considered abnormal and is related to deviation of the microfibrils (microfibril angle) from the longitudinal axis of the tracheid (Koehler 1954).

Six types of wood are most susceptible to excessive longitudinal shrinkage: reaction wood, abnormally light wood, springwood, wood near the pith of softwood trees or juvenile wood, wood in fast-growth conifers, and cross-grained wood (Koehler 1954). In conifers, reaction wood (compression wood), juvenile wood, and cross grain have been associated with excessive lumber warpage (Cockrell 1949, Dadswell 1958, Koehler 1938, Meylan 1968, Meylan and Probine 1969, Paul 1957, Pillow and Luxford 1937, and Shelly et al. 1979). Recent literature on causes of warping of young-growth ponderosa pine include Barger and Ffolliott (1976), Voorhies (1971, 1972, 1982), and Voorhies and Groman 1982.

Research to reduce warpage of studs has focused on drying and sawing methods. Studs with a top load restraint of 200 pounds per square foot were air-dried, kiln-dried at conventional temperatures, and kiln-dried at high temperatures. The studs kiln-dried at conventional temperatures yielded the greatest number meeting grade requirements (Arganbright et al. 1978). Blake and Voorhies (1980) did not find any difference in grade recovery between drying schedules using conventional and high temperatures in kiln-drying studs from young-growth ponderosa pine. Koch (1974) found that a high temperature kiln schedule with load restraints reduced bow and twist; but, serrated stickers were needed to minimize crook in southern pine studs. Maeglin and Boone (1983) showed that the grade yield of studs from small ponderosa pine logs by the Saw-Dry-Rip method can be substantially increased, compared to conventional sawing and drying at sawmills.

Study Objectives

The overall objective of this study was to observe how warp in lumber from young growth ponderosa pine is related to growing site, tree and wood characteristics, and ultimate moisture content of the dried lumber.

Two of the study's specific objectives are reported here.

1. Estimate the effects of site class, tree diameter, log size and position in the tree, and moisture content specifications upon degrade and warp in studs after:
   a. Initial kiln drying to either 19% or 15% moisture content.
   b. Additional drying to 9% and 6% moisture content. The additional drying was to simulate the effects of subsequent drying on warp development during unrestrained storage and at the job site.
2. Determine if studs sawed from the top logs of larger trees degrade and warp differently than those of the same size logs from smaller trees.

Methods

Study Areas and Tree Selection

A total of 82 young growth, "black bark" ponderosa pine trees were sampled at two sites on the Santa Fe National Forest, in northern New Mexico. These trees were (visually) selected to be representative of those to be harvested in the area. One-half of the trees were selected from a low index site; the remainder were chosen from a high index site. The number of trees selected in each diameter class on each site were:

Diameter class	Number of trees
inches d.b.h.	
9	12
10	8
11	6
12	5
13	5
14	5

The trees on the low index site were collected from the top of Alamitos Mesa (T. 20N, R. 6E, Sec. 27), on the Espanola Ranger District. The area has a site index of 55, a slope of less than 5% exposed to the east, and a soil of thin pumice. The trees on the high index site were collected near the Mud Springs Road (T. 26N., R1E, S29), on the Cuba Ranger District. This area has a site index of 100. Characteristics of the sample trees are shown in table 1. All of the sawlogs were grade 5, typically having many live and dead branches, branch stubs, and overgrown branches (Gaines 1962).

Trees were selected and identified by numbering them. Diameter at breast height was measured and recorded, as were grade of the logs in the standing tree, and lean. The trees were felled, limbed, and measured for total height. Five trees for each diameter class, at each site were sampled for the microfibril angle determinations. One-inch disks were sawn from the bottom and top of the tree length log and a ½-inch diameter increment core was extracted from the mid-length. The tree length logs were skidded to a landing, were bucked into 8-foot lengths, and were tagged with a tree and log number. The Colorado State Forest Service sawed the logs into studs in Fort Collins. The logs were end coated with a commercial paraffin water repellent to prevent end drying during a two month storage period before sawing.

Sawing

The 293 logs were separated by small end diameter inside bark to facilitate sawing. Diameter groups were as follows:

Groups	Small-end d.i.b	
	Mean ± SD	Number of logs
	inches	
1	5.9 ± 0.5	53
2	7.1 ± 0.4	77
3	8.1 ± 0.4	56
4	9.0 ± 0.4	44
5	10.3 ± 0.6	58
6	12.1 ± 0.3	5

The logs were sawn using methods that followed industry practices. Log groups 1, 2, and 3 were sawn on a portable scragg mill, and groups 4, 5, and 6 on a circular sawmill, into 4-inch cants and 2-inch flitches. The four saw scragg mill produced a 4-inch cant from the center and 2-inch flitches from the sides of the logs. The 4-inch cants were passed through a circular gang saw and were ripped into studs 2 inches wide. The 2-inch flitches were passed through the same circular gang saw and were ripped into studs 4 inches wide. The studs were identified as to tree and log number by spraying the log ends with different colored paints before sawing and by assigning a log number to each stud. The studs, after passing through the circular gang saw, were alternately stacked into four solid lumber piles to provide a uniform distribution of studs into 4 kiln charges. Each pile was wrapped with polyethylene film to prevent loss of moisture content before kiln drying.

Kiln Drying

The four piles of lumber were assigned numbers 1 through 4. Piles 1 and 3 were kiln dried to 19% moisture content (MC); piles 2 and 4 were kiln dried to 15% MC. These two moisture contents are standard specifications described by the Western Wood Products Association (1981). The standards state that any lumber surfaced at a moisture content of 19% or less may be stamped "S-DRY", and any lumber surfaced at a moisture content of 15% or less may be stamped "MC 15."

Table 1.—Characteristics of sample trees on low and high index sites.

Characteristics	Site	
	Low	High
	mean ± SD[1]	
Diameter (inches d.b.h.)	11.4 ± 1.9	11.4 ± 1.7
Total height (feet)	46.4 ± 6.3	59.4 ± 11.2
Height to 4-inch top d.i.b. (feet)	36.2 ± 6.8	47.4 ± 10.9
Height to 6-inch top d.i.b. (feet)	30.5 ± 7.3	39.5 ± 10.8
Volume, gross scale of logs (cubic feet)	10.8 ± 5.5	13.6 ± 7.0
No. of 8-foot logs per tree	3.1 ± 0.9	4.0 ± 1.2
Age at stump (years)	76 ± 19	78 ± 24
Lean (degrees)	2.2 ± 1.9	2.2 ± 1.9

[1]*Each mean and standard deviation is based on a sample of 41 trees.*

Each of the four kiln charges was dried following time chedule AS11-BK6 (Rasmussen 1961). Although com- nercial schedules vary from mill to mill, depending on iln type and performance and lumber condition, this chedule closely approached the condition that many perators in the area were trying to achieve. This sched- le follows.

Time	Temperature	
	Dry bulk	Wet bulb
hours	°F	
0-12	165	150
12-24	170	155
24-36	175	155
36-48	180	160
48-60	190	165
60-72	190	165
72-Final	200	170

The studs were dried in the Wood Science Laboratory iln at Colorado State University (fig. 1). This kiln is team heated and has two four-speed reversible fans nd a capacity of approximately 2,000 board feet. The iln is equipped with a Delmhorst Kil-Mo-Trol[2] which vas used to monitor the charge and determine when to egin equalization. Because studs normally are not esawn, no conditioning treatment was included in the iln runs. Equalizing was terminated when each of the ix in-place meter probes gave a reading which was vithin 3% of the target moisture content. Equalizing conditions and times are shown in table 2. For all four charges, the average initial moisture contents were above fiber saturation point, based upon the initial meter readings.

After drying, the studs were planed on four sides, on a commercial planer, to standard 1 1/2-inch × 3 1/2-inch size. Then they were examined for lumber grade, crook, bow, twist, cup, grain angle, number of knots, size of largest knot, and end split.

[2]*Trade and company name are used for the benefit of the reader nd do not imply endorsement or preferential treatment by the U.S. epartment of Agriculture.*

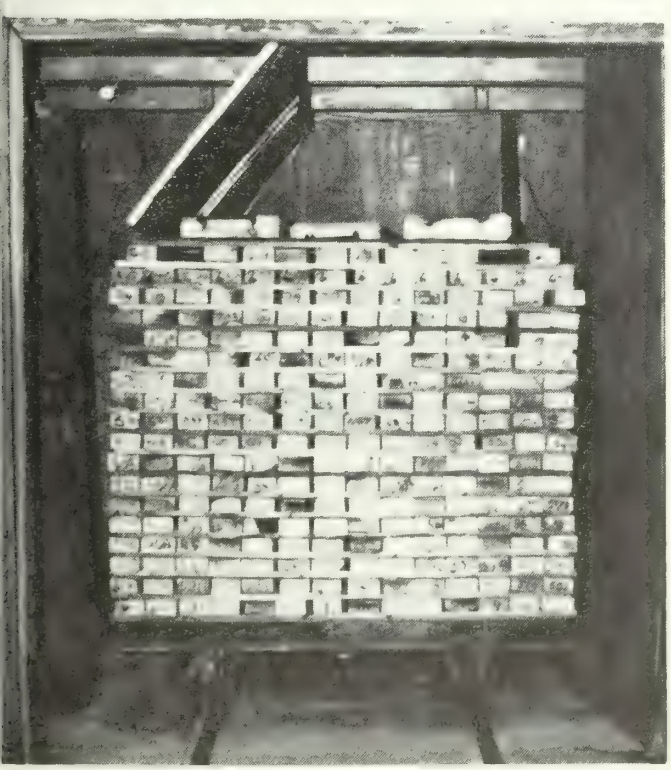

Figure 1.—Laboratory kiln with charge of stickered studs.

Subsequent Drying

Because much lumber produced in the Southwest is used in areas with low equilibrium moisture content condition, the studs were subsequently dried in two steps to 9% and then to 6% MC. At each of these moisture contents, the studs were regraded and measurements were taken for crook, bow, twist, cup, and end split. Kiln drying conditions were relatively mild (100°F dry bulb and 84°F wet bulb for 9%; 100°F dry bulb and 74°F wet bulb for 6%) in order to simulate conditions of lumber in storage or on a job site.

Also, as part of this simulation, the lumber was placed on a rack in the kiln, which allowed unrestricted shrinkage in each stud (fig. 2). Although in actual conditions, most of the lumber in a storage pile would be subject to some restraint, the conditions for this study were selected to give a "worst condition" situation. Attainment of the desired final moisture content was determined by a portable resistance-type moisture meter. Sample readings were taken periodically, and the drying was stopped when the readings were within 1% of the target moisture content.

Grading and Measurements

The studs were graded STUD, ECONOMY, or CULL, and the crook, bow, twist, cup, grain angle, size of largest knot, and end split were measured as defined by the Western Wood Products Association (1981). Crook is a deviation edgewise from a straight line drawn from end to end of the stud. It is measured at the greatest distance from the straight line. Bow is deviation flatwise from a straight line drawn from end to end and is measured at the point of greatest distance from the straight line. Twist is a deviation flatwise or a combination of flatwise and edgewise deviation in the form of a curl and is measured by clamping an end of the stud on a table and measuring the maximum distance that a lower corner at the other end is above the table. Cup is a deviation in the face of a piece from a straight line drawn from edge to edge and is measured as the greatest distance from the straight line. The width of the knot is measured as the distance between two lines touching the edge of the knot on the wide face and parallel to the edge of the stud. The slope of grain is determined with a scribe and is measured as the deviation of wood fiber on the wide face from a line parallel to the edges of the stud. End split is measured as the length of the split parallel to the edge of the stud.

Table 2.—Drying time, desired final moisture content (percent of oven-dry weight), and equalizing conditions of dry and wet bulb and time for the four kiln charges.

Charge	Drying time	Desired final moisture content	Equalizing conditions		
			Dry bulb	Wet bulb	Time
	hours		---------- °F ----------		*hours*
1	48	15	180	175	8
2	36	19	175	173	15
3	36	15	180	175	12
4	36	19	175	173	11

Analysis

The effects of growing site, tree diameter, log size and position, and extent of drying lumber grade were estimated using log linear models (Bishop et al. 1975). The effects of these variables upon amount of crook, bow, and twist after drying were determined by factorial analysis of variance. Because practical amounts of cup occurred in only a few studs during drying, it was omitted from the analysis. The term significant indicates statistical significance at the 0.05 level.

Figure 2.—Rack separating studs to permit unrestricted movement during drying to 9% and 6 % moisture content.

Results and Discussion

Growing Site

Site index was not significantly related to the percentage of studs in the different lumber grades or to the amount of crook, bow, and twist in the studs (table 3). When studs were dried from 19% or 15% moisture content (MC) to 9% and 6%, the grade of the lumber dropped. The proportion of STUD pieces dropped from 52% to 37% to 27%. The proportion of ECONOMY pieces increased from 48% to 54% to 56%; and cull increased from 0% to 9% to 17%.

When the studs were dried from 19% or 15% MC to 9% and 6%, the average crook increased from 4/16 to 5/16 to 6/16 inch, the average bow from 5/16 to 7/16 to 9/16 inch, and average twist from 4/16 to 6/16 to 7/16 inch.

Warpage varied considerably among both between and within categories. The similar values of average warp and percentage of studs in the different lumber grades between sites 55 and 100 may be partially attributed to the characteristics of the trees. As noted before, each log in the study regardless of site was a Grade 5 log. The logs had many limbs, limb stubs, and overgrown limbs.

Tree Diameter

Tree diameter did significantly affect the percentage of studs recovered in the different lumber grades and the amount of crook, bow, and twist in the studs. The percentage yield of lumber grade for trees 9, 10, and 11 inches d.b.h. was more adversely affected by further drying than that for trees with 12, 13, and 14 inches d.b.h. (table 4). The percentage of cull studs in the 9-, 10-, and 11-inch d.b.h. trees was significantly greater, about twice that of the 12-, 13-, and 14-inch d.b.h. trees when dried to 9% and 6% MC. The 9-inch d.b.h. trees had the lowest yield of STUD grade and the highest yield of cull studs after kiln drying and further drying. The 13-inch d.b.h. trees had the highest recovery of STUD grade studs.

Crook after kiln drying was similar for all tree diameters, with averages ranging from 4/16 to 5/16 inch. Average crook after further drying increased to a maximum of 7/16 inch at 9% MC for 11-inch d.b.h. trees and

Table 3.—Percentage of studs in each lumber grade and warp of studs sawn from trees sampled in areas with different site index and kiln dried to different moisture contents (percent of oven-dry weight).[1]

Moisture content	Site index	Lumber grade			Warp—1/16 inch		
		Stud	Economy	Cull	Crook	Bow	Twist
		percent			*mean ± SD*		
After kiln drying	55	52	48	0	4.1 ± 3.6	5.2 ± 4.6	3.6 ± 3.5
	100	52	48	0	4.2 ± 3.6	4.9 ± 4.2	4.0 ± 3.3
	combined	52	48	0	4.1 ± 3.6	5.0 ± 4.4	3.8 ± 3.4
9%	55	37	51	12	5.2 ± 5.1	7.0 ± 5.7	5.7 ± 5.0
	100	37	56	7	5.1 ± 5.2	6.9 ± 6.5	5.9 ± 4.4
	combined	37	54	9	5.1 ± 5.1	7.0 ± 6.2	5.8 ± 4.7
6%	55	28	53	19	6.6 ± 6.4	9.1 ± 7.6	6.8 ± 5.6
	100	27	59	14	6.1 ± 6.2	8.9 ± 8.0	7.0 ± 5.2
	combined	27	56	17	6.3 ± 6.3	9.0 ± 7.8	7.0 ± 5.4

[1]*The percentage values are based on 382 studs from 41 trees sampled in an area with site index 55 and 483 studs from 41 trees with site index 100.*

Table 4.—Percentage of studs in each lumber grade and warp of studs sawn from trees with different d.b.h. and kiln dried to different moisture contents (percent of oven-dry weight).[1]

Moisture content	Tree d.b.h.	Lumber grade			Warp—1/16 inch		
		Stud	Economy	Cull	Crook	Bow	Twist
	inches	*percent*			*mean ± SD*		
After kiln drying	9	39	61	0	3.9 ± 3.3	7.2 ± 5.1	5.1 ± 4.2
	10	51	49	0	4.3 ± 4.1	5.6 ± 4.9	3.8 ± 3.0
	11	47	53	0	4.9 ± 4.7	4.7 ± 3.8	3.9 ± 3.1
	12	53	47	0	3.6 ± 3.2	5.0 ± 4.8	3.9 ± 3.2
	13	62	38	0	3.8 ± 3.0	4.0 ± 3.6	3.5 ± 3.2
	14	54	46	0	4.4 ± 3.6	4.6 ± 3.9	3.5 ± 3.5
9%	9	19	60	21	5.3 ± 4.2	10.5 ± 6.9	7.7 ± 5.3
	10	32	59	9	5.9 ± 6.0	8.4 ± 6.2	5.8 ± 3.9
	11	24	62	14	6.8 ± 8.2	8.2 ± 8.8	6.0 ± 4.6
	12	38	57	5	4.4 ± 4.1	6.3 ± 5.3	6.0 ± 4.5
	13	52	41	7	4.2 ± 3.5	5.2 ± 4.8	5.1 ± 4.2
	14	42	51	7	5.2 ± 4.6	5.7 ± 4.6	5.3 ± 5.0
6%	9	12	53	35	6.3 ± 4.7	13.8 ± 8.6	8.7 ± 6.5
	10	27	52	21	8.0 ± 7.9	10.1 ± 8.3	6.9 ± 4.8
	11	15	61	24	8.4 ± 10.0	10.6 ± 9.7	7.3 ± 5.3
	12	30	59	11	5.3 ± 4.9	8.5 ± 7.1	7.2 ± 5.0
	13	38	50	12	5.2 ± 4.5	7.0 ± 6.7	6.5 ± 5.1
	14	30	61	9	6.0 ± 5.1	7.4 ± 5.9	6.1 ± 5.5

[1]*The number of studs sampled for each tree d.b.h. are: 9 inches—105, 10 inches—124, 11 inches—103, 12 inches—148, 13 inches—179, and 14 inches—206.*

8/16 inch at 6% MC for the 10- and 11-inch d.b.h. trees. Marketing limits for crook are 4/16 inch for STUD grade and 1 inch for ECONOMY grade (Western Wood Products Association 1981). There was no apparent trend relating the amount of crook to tree diameter. Crook varied considerably within each tree diameter class (table 4).

Average bow after kiln drying ranged from 4/16 to 7/16 inch with the 9-inch d.b.h. trees having the greatest amount. Average bow for the 9-inch d.b.h. trees after further drying increased to a maximum of 11/16 inch at 9% MC and 14/16 inch at 6%. Marketing limits for bow are 12/16 inch for STUD grade and none for ECONOMY grade (Western Wood Products Association 1981). Considerable variation of bow was observed within each tree diameter class.

Twist was similar to bow—the 9-inch d.b.h. trees had the greatest amount when compared to the other size trees. The average twist of the 9-inch d.b.h. trees ranged from 5/16 inch after kiln drying to 8/16 inch at 9% MC

and 9/16 inch at 6% MC. Marketing limits for twist are 6/16 inch for STUD grade and 1 inch for ECONOMY grade (Western Wood Products Association 1981). Twist also varied considerably within tree diameter class.

Moisture Content Specification

Drying studs with different moisture content specifications did not significantly affect the percentage of studs in the different lumber grades. Drying studs with different moisture content specifications also did not significantly affect the amount of crook, bow, and twist, when tree diameter was accounted for (tables 5, 6). The percentage recovery of lumber grade and warp measurements for the different combinations of moisture content specification, diameter, and log position are shown in tables A1 through A4.

Log Size and Position in Tree

Log position in the trees was not a significant indicator of lumber grade and warp when log diameter (d.i.b.) was accounted for. The 5- and 6-inch logs had a lower percentage of studs in STUD grade than the 7- through 12-inch logs after kiln drying (table 7). The 5- through 8-inch logs had a lower percentage of studs in STUD grade and a higher percentage of cull studs than the 9- through 12-inch logs after drying to 9% MC. Similarly, the 5-, 6-, and 7-inch logs had a lower percentage of studs in STUD grade and a higher percentage of cull studs than the 8- through 12-inch logs after drying to 6% MC.

A direct relationship of amount of crook with log diameter was not apparent (table 7). Generally, the 5- through 8-inch logs had more bow than the 9- through 12-inch logs after each drying condition. Similarly, the 5-, 6-, and 7-inch logs had more twist than the 8- through 12-inch logs. Research on young growth ponderosa pine has shown that butt logs have more crook and less twist than upper logs (Blake and Voorhies 1980, Maeglin and Boone 1983).

A separate analysis was performed to determine if studs from small logs of big trees warped differently than those from small logs of small trees. Analysis of 263 studs from logs of 8-inch d.i.b. and less indicated that:

1. The percentage of studs in each lumber grade is affected by moisture content, but is unrelated to tree size (diameter breast high) after kiln drying (table 8).
2. The studs from smaller trees did not warp more than those from the larger trees (table 8).

Conclusion

The results of this study indicate that a difference in site index from 55 to 100 for young growth "black jack" ponderosa pine does not affect either the grade or the amount of crook, bow, and twist of lumber kiln dried to commercial moisture specifications (S-DRY or MC15) and further dried to 9% and 6% MC. Tree diameter, however, does affect lumber grade recovery; 9-inch

Table 5.—Percentage of studs in each lumber grade and warp of studs sawn from trees with different d.b.h. and kiln dried to S-DRY specification and subsequently dried to 9% and 6% moisture content (percent of oven-dry weight).[1]

Moisture content	Tree d.b.h.	Lumber grade			Warp—1/16 inch		
		Stud	Econ	Cull	Crook	Bow	Twist
	inches	*percent*			*mean ± SD*		
After kiln drying	9	38	62	0	4.1 ± 3.3	7.4 ± 5.5	5.2 ± 4.6
	10	58	42	0	4.6 ± 5.0	4.8 ± 4.1	3.8 ± 3.0
	11	47	53	0	4.7 ± 5.3	4.8 ± 4.0	4.2 ± 3.2
	12	63	37	0	3.0 ± 2.5	4.4 ± 4.6	3.3 ± 2.8
	13	63	37	0	3.3 ± 2.7	3.8 ± 3.4	3.6 ± 3.1
	14	60	40	0	3.9 ± 3.1	4.2 ± 3.4	3.7 ± 3.6
9%	9	21	62	17	5.8 ± 4.7	10.2 ± 6.1	7.9 ± 5.9
	10	31	61	8	6.5 ± 7.4	8.8 ± 6.0	6.1 ± 4.0
	11	20	65	15	7.5 ± 10.7	7.8 ± 4.9	6.9 ± 5.4
	12	40	56	4	3.9 ± 2.9	6.7 ± 5.6	5.5 ± 4.2
	13	52	40	8	4.2 ± 3.8	6.0 ± 5.6	5.5 ± 4.7
	14	43	47	10	5.1 ± 5.3	5.9 ± 4.7	5.9 ± 5.5
6%	9	11	57	32	7.0 ± 5.3	15.1 ± 8.2	9.3 ± 7.5
	10	24	55	21	9.5 ± 9.7	11.0 ± 8.3	7.5 ± 5.2
	11	6	65	29	10.7 ± 12.8	11.2 ± 6.9	8.7 ± 6.0
	12	29	63	8	5.4 ± 3.7	9.5 ± 7.9	6.9 ± 5.0
	13	29	56	15	6.0 ± 5.2	8.5 ± 8.1	7.1 ± 5.3
	14	23	63	14	6.5 ± 6.0	8.3 ± 6.1	6.9 ± 6.3

[1]*The number of studs sampled for each tree d.b.h. are: 9 inches—47, 10 inches—67, 11 inches—51, 12 inches—75, 13 inches—88, and 14 inches—100.*

Table 6.—Percentage of studs in each lumber grade and warp of studs sawn from trees with different d.b.h. and kiln dried to MC-15 specification and subsequently dried to 9% and 6% moisture content (percent of oven-dry weight).[1]

Moisture content	Tree d.b.h.	Lumber grade			Warp—1/16 inch		
		Stud	Econ	Cull	Crook	Bow	Twist
	inches	*percent*			*mean ± SD*		
After kiln drying	9	40	60	0	3.8 ± 3.3	7.0 ± 4.8	4.9 ± 3.8
	10	42	58	0	3.9 ± 2.8	6.6 ± 5.5	3.8 ± 3.1
	11	46	54	0	5.2 ± 4.0	4.5 ± 3.7	3.7 ± 3.0
	12	43	57	0	4.3 ± 3.6	5.6 ± 5.0	4.4 ± 3.4
	13	60	40	0	4.1 ± 3.2	4.1 ± 3.7	3.5 ± 3.3
	14	48	52	0	4.9 ± 4.0	4.9 ± 4.2	3.3 ± 3.4
9%	9	17	59	24	5.0 ± 3.8	10.8 ± 7.6	7.5 ± 4.8
	10	33	56	11	5.1 ± 3.7	7.8 ± 6.4	5.4 ± 3.8
	11	29	59	12	6.0 ± 4.6	8.6 ± 11.4	5.0 ± 3.5
	12	36	59	5	4.9 ± 5.0	5.8 ± 5.1	6.5 ± 4.7
	13	52	42	6	4.1 ± 3.2	4.5 ± 3.8	4.8 ± 3.8
	14	41	54	5	5.2 ± 3.8	5.5 ± 4.5	4.7 ± 4.4
6%	9	14	48	38	5.7 ± 4.2	12.7 ± 8.7	8.2 ± 5.6
	10	30	49	21	6.3 ± 4.4	9.1 ± 8.2	6.3 ± 4.4
	11	23	58	19	6.2 ± 5.3	9.9 ± 11.8	5.8 ± 4.1
	12	30	56	14	5.2 ± 5.8	7.4 ± 6.1	7.6 ± 5.1
	13	47	44	9	4.3 ± 3.6	5.5 ± 4.7	6.0 ± 4.8
	14	37	58	5	5.6 ± 4.1	6.5 ± 5.6	5.3 ± 4.5

[1]*The number of studs sampled for each tree d.b.h. are: 9 inches—58, 10 inches—57, 11 inches—52, 12 inches—73, 13 inches—91, and 14 inches—106.*

Table 7.—Percentage of studs in each lumber grade and warp of studs sawn from logs with different d.i.b. and kiln dried and subsequently dried to 9% and 6% moisture content (percent of oven-dry weight).[1]

Moisture content	Log d.i.b. small end	Lumber grade			Warp—1/16 inch		
		Stud	Econ	Cull	Crook	Bow	Twist
	inches	*percent*			*mean ± SD*		
After kiln drying	5	27	73	0	3.8 ± 2.8	8.4 ± 5.6	6.1 ± 4.8
	6	38	62	0	3.7 ± 3.1	6.4 ± 4.5	5.1 ± 3.6
	7	48	52	0	4.3 ± 3.4	5.8 ± 4.8	4.4 ± 3.6
	8	50	50	0	4.7 ± 4.6	4.8 ± 3.8	3.5 ± 3.0
	9	60	40	0	4.0 ± 3.6	4.1 ± 4.1	3.3 ± 3.0
	10	63	37	0	3.7 ± 2.6	4.3 ± 4.1	3.3 ± 3.3
	11	54	46	0	4.4 ± 4.1	4.1 ± 3.9	3.6 ± 3.0
	12	50	50	0	4.3 ± 2.7	5.2 ± 4.3	2.5 ± 2.5
9%	5	6	70	24	6.2 ± 3.0	12.0 ± 4.9	10.0 ± 5.4
	6	21	62	17	4.6 ± 3.6	9.7 ± 6.7	7.3 ± 5.0
	7	26	62	13	5.6 ± 4.8	8.4 ± 6.6	6.6 ± 4.8
	8	32	61	7	5.8 ± 5.7	7.3 ± 5.4	5.9 ± 4.5
	9	50	42	8	4.7 ± 6.3	5.2 ± 6.6	4.9 ± 4.1
	10	54	42	4	4.3 ± 3.8	5.1 ± 4.9	4.8 ± 4.5
	11	41	51	8	4.9 ± 4.0	6.0 ± 5.0	5.0 ± 3.7
	12	39	54	7	6.8 ± 7.1	6.3 ± 5.2	4.6 ± 4.2
6%	5	3	52	45	6.8 ± 3.9	15.0 ± 7.9	11.5 ± 6.8
	6	13	62	25	5.9 ± 4.4	12.3 ± 8.4	8.4 ± 6.0
	7	16	57	27	7.3 ± 6.5	10.6 ± 8.2	7.9 ± 5.2
	8	28	56	16	7.3 ± 7.4	9.2 ± 7.0	7.3 ± 5.6
	9	36	53	11	5.8 ± 7.0	7.0 ± 8.0	6.0 ± 4.6
	10	41	53	6	4.6 ± 4.0	6.9 ± 6.8	5.8 ± 5.3
	11	29	64	7	5.8 ± 4.1	7.6 ± 6.7	6.0 ± 4.2
	12	25	61	14	8.8 ± 9.3	6.9 ± 5.2	5.0 ± 4.2

[1]*The number of studs sampled for each log d.i.b. are: 5 inches—33, 6 inches—76, 7 inches—143, 8 inches—180, 9 inches—181, 10 inches—141, 11 inches—83, and 12 inches—28.*

Table 8.—Percentage of studs in each lumber grade and warp of studs sawn from logs of 8-inch diameter or less from trees with different d.b.h. and kiln dried to different moisture contents (percent of oven-dry weight).[1]

Moisture content	Tree d.b.h.	Lumber grade			Warp—1/16 inch		
		Stud	Econ	Cull	Crook	Bow	Twist
	inches	*percent*			*mean ± SD*		
After kiln drying	9	41	59	0	3.9 ± 3.3	7.1 ± 5.1	5.0 ± 4.2
	10	43	57	0	3.9 ± 3.2	6.0 ± 5.1	4.2 ± 3.3
	11	50	50	0	3.9 ± 2.9	5.1 ± 3.9	4.9 ± 3.1
	12	44	56	0	3.0 ± 2.5	6.6 ± 4.8	5.4 ± 3.0
	13	42	58	0	4.1 ± 3.0	4.8 ± 4.1	5.6 ± 4.0
	14	25	75	0	6.7 ± 4.1	6.8 ± 3.8	6.3 ± 5.4
9%	9	20	58	22	5.4 ± 4.3	10.3 ± 6.7	7.5 ± 5.3
	10	23	68	9	5.2 ± 4.3	8.7 ± 6.1	6.3 ± 4.0
	11	25	62	13	5.9 ± 5.1	8.7 ± 8.3	7.2 ± 4.7
	12	15	78	7	3.4 ± 2.4	9.1 ± 5.7	7.6 ± 4.2
	13	32	47	21	5.0 ± 4.0	7.2 ± 5.3	8.8 ± 6.3
	14	6	69	25	5.2 ± 4.4	9.1 ± 6.3	9.3 ± 8.1
6%	9	13	53	34	6.4 ± 4.8	13.6 ± 8.5	8.3 ± 6.2
	10	21	56	23	7.3 ± 5.8	10.4 ± 8.2	7.8 ± 4.9
	11	9	63	28	6.8 ± 7.7	10.3 ± 9.2	8.6 ± 4.9
	12	4	74	22	5.3 ± 3.4	12.1 ± 6.5	9.4 ± 4.0
	13	16	53	31	7.7 ± 7.6	10.3 ± 7.4	11.1 ± 6.6
	14	6	63	31	9.1 ± 4.7	11.3 ± 8.7	9.4 ± 8.2

[1]*The number of studs sampled for each tree d.b.h. are: 9 inches—101, 10 inches—68, 11 inches—32, 12 inches—27, 13 inches—19, and 14 inches—16.*

d.b.h. trees had the lowest grade recovery, and the 9-, 10-, and 11-inch d.b.h. trees yielded about twice the percentage of cull studs as the 12-, 13-, and 14-inch d.b.h. trees when dried to 9% and 6% MC. Lumber from 9-inch d.b.h. trees also bowed and twisted most during the different stages of drying.

Log position in the tree had little effect on lumber grade recovery and warp when log diameter was accounted for. The smaller logs yielded lower grade lumber with generally more warp than the larger logs. Kiln drying to either the S-DRY or MC15 specification did not affect the grade or lumber recovered or the amount of warp when tree diameter was accounted for.

The claim that studs from small top logs of larger trees do not lose grade or warp as much as those from small logs of smaller trees was not supported by the results of this study. The studs from logs 8 inches or less in diameter, regardless of location in the tree, had similar grades and warpage, and were affected only by moisture content.

The study indicates that growing young "black jack" ponderosa pine trees to a diameter greater than 11 inches would reduce the warpage of studs marketed in low humidity areas.

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Appendix

Tables on Percentage of Lumber Grade and Warp Measurements for Different Combinations of Moisture Content Specification, Diameter Breast Height and Log Position

Table A1.—Percentage of studs in each lumber grade sawn from trees with different d.b.h. and at different log positions and kiln dried to MC-15 specification and subsequently dried to 9% and 6% (percent of oven-dry weight).

Tree d.b.h.	Log position	Lumber grade at moisture content of: After kiln drying			9%			6%			No. of studs
		Stud	Econ	Cull	Stud	Econ	Cull	Stud	Econ	Cull	
inches		*percent*									
9	1	32	68	0	18	55	27	9	50	41	22
	2	50	50	0	21	58	21	21	50	29	24
	3	40	60	0	10	70	10	10	50	40	10
	4	0	100	0	0	50	50	0	0	100	2
10	1	60	40	0	48	48	4	40	52	8	25
	2	57	43	0	43	57	0	43	43	14	14
	3	7	93	0	7	64	29	7	50	43	14
	4	0	100	0	0	67	33	0	33	67	3
	5	0	100	0	0	100	0	0	100	0	1
11	1	43	57	0	29	47	24	19	52	29	21
	2	48	52	0	33	67	0	29	62	9	21
	3	57	43	0	29	71	0	14	72	14	7
	4	33	67	0	0	67	33	33	33	34	3
12	1	48	52	0	48	48	4	44	44	12	25
	2	33	67	0	33	67	0	22	61	17	18
	3	35	65	0	35	53	12	29	59	12	17
	4	71	29	0	14	86	0	14	71	15	7
	5	0	100	0	0	67	33	0	67	33	3
	6	100	0	0	50	50	0	50	50	0	2
	7	0	100	0	0	100	0	0	100	0	1
13	1	68	32	0	55	45	0	59	41	0	22
	2	58	42	0	38	54	8	38	54	8	24
	3	63	37	0	71	25	4	58	34	8	24
	4	53	47	0	47	40	13	40	40	20	15
	5	50	50	0	33	67	0	17	66	17	6
	6	-	-	-	-	-	-	-	-	-	0
14	1	50	50	0	45	55	0	42	55	3	39
	2	45	55	0	38	52	10	35	55	10	29
	3	63	37	0	63	37	0	56	44	0	16
	4	35	65	0	29	65	6	18	82	0	17
	5	60	40	0	20	80	0	20	80	0	5
	6	0	0	0	0	0	0	0	0	0	0

Table A2.—Percentage of studs in each lumber grade sawn from trees with different d.b.h. and at different log positions, kiln dried to S-DRY specification and subsequently dried to 9% and 6% (percent of oven-dry weight).

Tree d.b.h.	Log position	Lumber grade at moisture content of: After kiln drying			9%			6%			No. of studs
		Stud	Econ	Cull	Stud	Econ	Cull	Stud	Econ	Cull	
inches		*percent*									
9	1	29	71	0	18	59	23	12	41	47	17
	2	41	59	0	35	47	18	12	65	23	17
	3	46	54	0	8	85	7	8	69	23	13
	4	–	–	–	–	–	–	–	–	–	0
10	1	65	35	0	27	62	11	15	58	27	26
	2	61	39	0	48	43	9	39	44	17	23
	3	36	64	0	18	82	0	18	64	18	11
	4	60	40	0	20	80	0	20	80	0	5
	5	50	50	0	0	100	0	0	50	50	2
11	1	40	60	0	15	60	25	5	60	35	21
	2	62	38	0	15	77	8	0	77	23	14
	3	55	45	0	27	55	18	18	46	36	11
	4	20	80	0	40	60	0	0	80	20	5
12	1	71	29	0	48	52	0	38	62	0	21
	2	73	27	0	50	46	4	36	59	5	22
	3	56	44	0	39	50	11	33	44	23	18
	4	43	57	0	14	86	0	0	86	14	7
	5	50	50	0	17	83	0	0	100	0	6
	6	–	–	–	–	–	–	–	–	–	0
	7	0	100	0	0	100	0	0	100	0	1
13	1	64	36	0	60	32	8	28	60	12	25
	2	80	20	0	68	24	8	36	52	12	25
	3	63	37	0	44	56	0	44	50	6	16
	4	47	53	0	40	47	13	13	67	20	15
	5	17	83	0	17	66	17	17	33	50	6
	6	100	0	0	0	100	0	0	100	0	1
14	1	63	37	0	42	47	11	16	71	13	37
	2	63	37	0	54	37	8	29	63	8	24
	3	60	40	0	50	45	5	35	60	5	20
	4	64	36	0	27	64	9	18	55	27	11
	5	50	50	0	25	75	0	25	50	25	4
	6	0	100	0	0	25	75	0	25	75	4

Table A3.—Warp of studs sawn from trees with different d.b.h. and at different log position, kiln dried to MC-15 specification, and subsequently dried to 9% and 6% moisture content (percent of oven-dry weight).

Tree d.b.h.	Log position	Warp -1/16 inch at moisture content of									No. of studs
		After kiln drying			9%			6%			
		Crook	Bow	Twist	Crook	Bow	Twist	Crook	Bow	Twist	
inches		*mean ± SD*									
9	1	4.5 ± 4.4	7.1 ± 5.5	3.8 ± 3.9	5.6 ± 4.9	12.0 ± 8.3	6.1 ± 5.1	7.0 ± 5.3	14.0 ± 8.9	6.8 ± 5.2	22
	2	3.0 ± 2.1	6.2 ± 3.9	5.0 ± 2.5	3.9 ± 2.7	9.5 ± 7.1	7.5 ± 3.5	4.5 ± 3.1	11.2 ± 7.7	7.9 ± 4.4	24
	3	3.9 ± 2.6	7.6 ± 5.3	6.7 ± 5.3	5.3 ± 2.8	10.8 ± 7.8	9.1 ± 5.1	5.3 ± 2.7	14.0 ± 11.2	10.5 ± 5.6	10
	4	6.0 ± 2.8	11.0 ± 1.4	8.0 ± 5.7	9.0 ± 4.2	11.5 ± 6.4	15.5 ± 4.9	9.5 ± 6.4	11.0 ± 9.9	17.0 ± 15.6	2
10	1	3.8 ± 2.5	4.8 ± 4.6	1.9 ± 1.5	4.4 ± 3.2	6.4 ± 4.6	3.6 ± 2.8	5.0 ± 3.2	7.9 ± 7.1	3.9 ± 2.3	25
	2	4.3 ± 3.6	5.6 ± 4.7	3.1 ± 2.5	5.4 ± 4.4	6.0 ± 4.7	4.6 ± 3.3	6.1 ± 4.7	7.2 ± 6.5	5.9 ± 4.2	14
	3	3.6 ± 2.5	10.2 ± 6.2	7.0 ± 2.5	5.6 ± 3.6	11.4 ± 8.8	9.1 ± 3.1	7.4 ± 4.7	13.4 ± 10.5	10.9 ± 3.0	14
	4	2.7 ± 1.2	10.7 ± 6.1	8.0 ± 4.0	6.7 ± 4.6	12.0 ± 8.0	8.0 ± 4.0	12.0 ± 8.0	8.7 ± 9.9	8.0 ± 8.0	3
	5	8.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	7.0 ± 0.0	6.0 ± 0.0	0.0 ± 0.0	7.0 ± 0.0	3.0 ± 0.0	2.0 ± 0.0	1
11	1	5.9 ± 4.7	4.2 ± 3.7	3.1 ± 2.7	6.4 ± 4.6	10.1 ± 17.1	4.2 ± 2.1	7.3 ± 4.7	13.0 ± 17.0	5.1 ± 2.9	21
	2	5.3 ± 4.0	4.4 ± 3.6	3.1 ± 2.8	6.3 ± 5.0	7.0 ± 4.1	4.4 ± 3.4	6.7 ± 6.2	7.9 ± 6.0	5.5 ± 3.8	21
	3	4.3 ± 1.0	5.1 ± 3.6	5.1 ± 3.0	4.7 ± 4.4	9.7 ± 6.8	6.6 ± 4.3	3.7 ± 4.1	9.0 ± 6.4	7.3 ± 5.2	7
	4	2.0 ± 0.0	5.3 ± 6.1	7.3 ± 4.2	3.7 ± 2.1	5.7 ± 2.1	10.7 ± 6.4	1.7 ± 1.5	5.3 ± 6.1	10.0 ± 8.7	3
12	1	3.6 ± 3.1	5.6 ± 5.9	4.1 ± 3.8	4.8 ± 5.5	5.0 ± 5.7	5.7 ± 5.0	4.8 ± 6.8	6.3 ± 7.0	7.1 ± 5.6	25
	2	6.2 ± 5.3	4.9 ± 4.1	3.6 ± 3.1	5.4 ± 6.7	5.4 ± 4.3	5.3 ± 4.5	6.4 ± 7.7	7.2 ± 5.7	6.6 ± 3.9	18
	3	3.6 ± 1.7	5.5 ± 4.8	4.8 ± 3.4	4.8 ± 3.1	6.0 ± 4.5	7.5 ± 4.6	4.5 ± 3.1	6.7 ± 5.5	8.5 ± 5.9	17
	4	4.0 ± 2.8	4.6 ± 4.1	5.0 ± 3.3	5.6 ± 5.0	7.5 ± 4.3	7.3 ± 4.0	5.1 ± 3.8	9.9 ± 4.7	8.3 ± 5.1	7
	5	4.7 ± 3.1	11.7 ± 3.2	7.0 ± 3.6	4.7 ± 1.2	12.7 ± 7.0	10.7 ± 5.1	5.7 ± 2.1	14.0 ± 7.2	10.0 ± 5.3	3
	6	1.5 ± 0.7	5.0 ± 4.2	6.0 ± 0.0	3.0 ± 1.4	2.0 ± 0.0	9.0 ± 4.2	4.0 ± 0.0	9.0 ± 4.2	10.0 ± 5.7	2
	7	0.0 ± 0.0	8.0 ± 0.0	8.0 ± 0.0	4.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	2.0 ± 0.0	10.0 ± 0.0	6.0 ± 0.0	1
13	1	3.9 ± 2.1	3.4 ± 3.2	2.4 ± 2.5	3.6 ± 2.0	4.2 ± 3.2	3.6 ± 2.8	3.6 ± 2.2	3.9 ± 3.3	4.1 ± 3.2	22
	2	4.0 ± 2.0	4.8 ± 3.6	3.9 ± 2.6	4.5 ± 2.3	4.4 ± 3.4	4.9 ± 3.2	4.3 ± 2.4	6.2 ± 4.6	5.9 ± 3.3	24
	3	4.4 ± 2.9	3.1 ± 2.7	3.1 ± 3.0	3.8 ± 2.7	3.4 ± 3.0	4.0 ± 3.5	4.5 ± 3.4	4.7 ± 4.3	5.8 ± 5.5	24
	4	4.3 ± 5.9	5.4 ± 5.4	4.1 ± 3.8	4.9 ± 5.8	6.5 ± 5.3	6.5 ± 4.6	5.0 ± 6.5	8.1 ± 6.5	8.0 ± 5.7	15
	5	4.0 ± 3.5	5.2 ± 4.0	5.5 ± 6.3	3.8 ± 3.1	5.0 ± 3.9	7.5 ± 6.1	4.5 ± 3.3	4.7 ± 3.5	9.0 ± 7.3	6
	6	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	0
14	1	4.5 ± 3.4	5.3 ± 4.4	3.2 ± 2.8	5.5 ± 4.1	6.4 ± 4.7	4.4 ± 3.7	5.8 ± 4.5	7.8 ± 5.5	5.3 ± 3.8	39
	2	5.2 ± 5.5	4.7 ± 4.5	3.3 ± 3.8	4.9 ± 4.1	4.8 ± 4.5	4.8 ± 4.7	5.6 ± 4.3	5.6 ± 5.4	5.7 ± 5.6	29
	3	3.4 ± 1.8	4.0 ± 2.9	3.1 ± 3.5	3.9 ± 2.4	4.8 ± 3.6	4.4 ± 5.1	3.9 ± 2.3	4.6 ± 4.5	4.4 ± 3.9	16
	4	5.7 ± 3.0	4.5 ± 3.9	3.6 ± 3.5	6.1 ± 3.2	4.3 ± 3.5	5.5 ± 4.8	6.5 ± 3.6	4.8 ± 4.1	5.4 ± 4.4	17
	5	7.0 ± 6.0	6.4 ± 6.2	4.2 ± 4.9	5.2 ± 4.1	7.4 ± 6.2	5.8 ± 4.4	5.2 ± 2.4	9.8 ± 7.0	6.2 ± 4.5	5
	6	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	0

Table A4.—Warp of studs sawn from trees with different d.b.h. and at different log position, kiln dried to S-DRY specification, and subsequently dried to 9% and 6% moisture content (percent of oven-dry weight).

Tree d.b.h.	Log position	Warp -1/16 inch at moisture content of: After kiln drying			9%			6%			No. of studs
		Crook	Bow	Twist	Crook	Bow	Twist	Crook	Bow	Twist	
inches		*mean ± SD*									
9	1	5.4 ± 4.0	10.6 ± 6.0	4.5 ± 2.9	7.0 ± 6.6	12.4 ± 7.8	6.4 ± 5.1	8.8 ± 7.3	19.2 ± 8.6	8.4 ± 8.1	17
	2	3.3 ± 3.1	5.0 ± 3.8	5.3 ± 4.8	4.4 ± 3.2	8.0 ± 4.4	8.1 ± 6.3	6.2 ± 3.6	10.0 ± 5.7	8.8 ± 6.6	17
	3	3.5 ± 1.9	6.3 ± 4.8	6.2 ± 6.1	5.9 ± 2.8	10.2 ± 4.6	9.6 ± 6.4	5.9 ± 3.4	16.2 ± 7.4	11.2 ± 8.2	13
	4	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	0
10	1	5.0 ± 6.6	4.9 ± 4.5	3.8 ± 2.7	8.9 ± 10.0	10.2 ± 6.9	5.8 ± 4.0	12.7 ± 12.8	13.5 ± 9.3	7.7 ± 5.1	26
	2	4.1 ± 4.0	4.7 ± 4.2	3.4 ± 3.1	4.7 ± 5.2	7.3 ± 5.9	5.4 ± 3.8	7.5 ± 7.2	8.3 ± 8.4	6.3 ± 4.5	23
	3	5.2 ± 3.7	5.3 ± 4.3	4.8 ± 4.1	5.9 ± 5.0	8.1 ± 4.2	6.7 ± 4.0	7.5 ± 6.9	10.3 ± 4.8	7.7 ± 5.5	11
	4	2.4 ± 2.6	4.8 ± 2.4	3.4 ± 1.7	5.0 ± 2.0	11.8 ± 5.1	8.2 ± 3.3	7.8 ± 3.3	12.6 ± 8.0	10.4 ± 3.8	5
	5	6.5 ± 3.5	2.0 ± 0.0	4.0 ± 2.8	4.0 ± 2.8	6.5 ± 2.1	7.5 ± 7.8	6.5 ± 6.4	7.0 ± 1.4	10.0 ± 14.1	2
11	1	6.0 ± 7.4	4.7 ± 3.8	3.1 ± 2.3	9.9 ± 15.9	8.7 ± 4.8	5.2 ± 4.8	14.3 ± 17.8	12.0 ± 6.7	6.4 ± 5.1	21
	2	4.0 ± 3.1	4.5 ± 3.8	4.8 ± 3.6	6.4 ± 4.6	7.3 ± 4.5	9.9 ± 6.1	9.0 ± 5.8	12.4 ± 7.0	12.4 ± 6.0	14
	3	4.3 ± 3.8	4.3 ± 2.8	5.1 ± 3.7	7.0 ± 6.6	7.9 ± 6.3	7.0 ± 5.0	10.0 ± 10.5	10.2 ± 8.2	9.2 ± 6.1	11
	4	2.4 ± 0.9	4.6 ± 2.5	4.2 ± 3.9	3.0 ± 1.7	4.2 ± 2.5	5.8 ± 6.0	3.6 ± 3.3	5.8 ± 2.7	6.4 ± 7.1	5
12	1	3.0 ± 1.8	4.9 ± 5.7	2.2 ± 2.7	4.0 ± 2.9	7.2 ± 6.7	3.2 ± 3.2	5.1 ± 3.5	10.3 ± 10.3	3.6 ± 3.7	21
	2	2.5 ± 2.5	3.1 ± 3.6	3.1 ± 2.9	3.8 ± 2.8	4.7 ± 4.3	5.5 ± 4.0	5.2 ± 4.2	7.0 ± 5.7	6.7 ± 4.7	22
	3	2.6 ± 2.2	4.4 ± 4.5	4.3 ± 3.0	3.9 ± 2.8	7.2 ± 5.5	7.6 ± 5.1	5.9 ± 3.6	9.7 ± 6.6	9.9 ± 5.3	18
	4	4.6 ± 3.6	4.1 ± 4.3	2.9 ± 1.7	5.3 ± 4.5	5.7 ± 3.1	5.4 ± 4.1	7.3 ± 4.7	9.1 ± 6.9	8.3 ± 5.1	7
	5	4.5 ± 4.1	7.3 ± 4.1	4.5 ± 2.8	2.0 ± 1.8	11.5 ± 6.9	6.7 ± 3.1	3.7 ± 1.5	15.0 ± 8.6	8.7 ± 2.7	6
	6	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	-- ± --	0
	7	2.0 ± 0.0	8.0 ± 0.0	6.0 ± 0.0	4.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	14.0 ± 0.0	8.0 ± 0.0	1
13	1	3.0 ± 2.0	3.7 ± 3.3	3.4 ± 3.4	3.0 ± 2.4	6.1 ± 6.9	4.4 ± 4.0	4.9 ± 2.4	8.4 ± 9.4	5.8 ± 4.3	25
	2	3.0 ± 2.9	2.8 ± 3.5	3.0 ± 2.9	4.8 ± 5.0	5.0 ± 5.9	4.8 ± 4.1	5.0 ± 4.4	7.0 ± 8.6	6.4 ± 4.7	25
	3	3.0 ± 2.3	3.3 ± 1.4	2.5 ± 1.9	3.3 ± 2.1	5.3 ± 3.3	4.3 ± 4.3	4.7 ± 2.5	7.5 ± 6.2	5.9 ± 5.5	16
	4	3.7 ± 3.1	5.9 ± 4.1	5.4 ± 3.4	5.2 ± 4.6	6.1 ± 3.6	7.7 ± 5.2	8.9 ± 8.9	10.0 ± 6.2	9.8 ± 5.3	15
	5	6.3 ± 3.6	4.3 ± 3.9	5.5 ± 3.2	7.0 ± 3.8	10.0 ± 6.6	9.7 ± 6.4	11.1 ± 5.9	12.7 ± 8.7	11.7 ± 7.1	6
	6	3.0 ± 0.0	5.0 ± 0.0	3.0 ± 0.0	4.0 ± 0.0	16.0 ± 0.0	9.0 ± 0.0	6.0 ± 0.0	17.0 ± 0.0	10.0 ± 0.0	1
14	1	3.7 ± 2.9	3.9 ± 3.7	2.6 ± 2.3	6.0 ± 6.9	6.5 ± 4.8	4.8 ± 3.4	8.1 ± 8.6	8.3 ± 6.0	5.5 ± 3.7	37
	2	4.0 ± 3.0	4.1 ± 3.4	3.5 ± 3.3	4.4 ± 3.5	5.4 ± 4.1	5.0 ± 5.8	4.8 ± 2.4	7.4 ± 5.7	6.6 ± 7.1	24
	3	3.2 ± 2.4	3.9 ± 3.5	3.9 ± 3.9	3.5 ± 3.2	4.5 ± 4.2	5.9 ± 5.2	4.8 ± 3.0	6.9 ± 5.3	6.2 ± 5.8	20
	4	5.6 ± 4.1	4.1 ± 2.8	5.3 ± 4.8	6.3 ± 4.8	5.5 ± 3.7	9.3 ± 8.4	7.5 ± 4.6	9.3 ± 5.5	10.2 ± 9.1	11
	5	4.3 ± 5.2	5.7 ± 2.1	5.2 ± 2.2	5.8 ± 6.8	5.8 ± 2.1	7.7 ± 3.1	6.5 ± 5.3	8.5 ± 2.5	11.0 ± 6.2	4
	6	5.3 ± 2.8	8.3 ± 2.9	6.8 ± 7.3	6.5 ± 5.0	15.0 ± 8.2	9.8 ± 10.1	9.5 ± 5.5	21.0 ± 10.0	11.0 ± 11.6	4

Markstrom, Donald C., Craig E. Shuler, and Rudy M. King. 1984. Warpage of studs from young growth ponderosa pine from Northern New Mexico. USDA Forest Service Research Paper RM-257, 13 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

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Keywords: Warpage, forest products, *Pinus ponderosa*, lumber

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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United States
Department of
Agriculture

Forest Service

**Rocky Mountain
Forest and Range
Experiment Station**

Fort Collins,
Colorado 80526

**Research Paper
RM-258**

Effects of Clearcutting a Subalpine Forest in Central Colorado on Wildlife Habitat

Glenn L. Crouch

USDA Forest Service
Research Paper RM-258

March 1985

Effects of Clearcutting a Subalpine Forest in Central Colorado on Wildlife Habitat

Glenn L. Crouch, Principal Research Wildlife Biologist
Rocky Mountain Forest and Range Experiment Station[1]

Abstract

Clearcutting 3-acre circular blocks on average and moist sites increased understory plant production and cover, but caused few changes in species composition. Plant moisture and crude protein content, and digestibility also increased after logging; but, incidence of herbivore activity varied among species.

[1]*Headquarters is in Fort Collins, in cooperation with Colorado State University.*

Effects of Clearcutting a Subalpine Forest in Central Colorado on Wildlife Habitat

Glenn L. Crouch

Management Implications

Subalpine forests in the central Rocky Mountains are regarded as prime producers of water for downstream users. The accepted practice for enhancing water flow from conifer stands is clearcutting relatively small blocks in such a way that interception losses are modified, deposition of snow is increased in the clearcut blocks, and the melting regime is altered (Hibbert 1979, Troendle 1983).

Monitoring understory vegetation before and after clearcutting 12, well-distributed, 3-acre circular blocks comprising about 35% of a 100-acre watershed indicated that plant production generally increased on average sites, and made major gains on one moist site. Big game forage quality characteristics also improved after logging. Herbivore activity varied among the species.

This logging practice was considered to be beneficial for big game and other animal species requiring or favoring forest openings. Impacts were evaluated as neutral or only mildly negative for animals requiring or favoring closed-canopy or old-forest stands, such as cavity-nesters and snowshoe hare, because the openings were small, and relatively few. Removal of the intervening uncut timber probably would increase big game forage, but could be detrimental by decreasing cover availability. Closed-canopy dwellers also would be adversely affected by a large decrease in mature timber.

INTRODUCTION

Much of the informaton on water production from forests in the central Rocky Mountains has been developed at the USDA Forest Service's Fraser Experimental Forest, in Colorado. Research at the Experimental Forest dates from the 1930's, with the major experimental effort until recently, consisting of the Fool Creek watershed study. For this study, 278 acres of mature subalpine timber on 550 acres of commercial forest land were clearcut in alternate variable width strips, from 1954 through 1956, to increase streamflow from the watershed (Alexander and Watkins 1977).

Two years after logging on Fool Creek, more mule deer (*Odocoileus hemionus*) fecal groups were found on clearcut than on uncut strips, and production of some plant species was somewhat greater on the clearcut areas (Porter 1959). Fecal counts in 1966, about 10 years later, showed nearly three times more droppings per acre on clearcut strips than on adjacent uncut areas (Wallmo 1969).

Studies of deer feeding preferences and amounts and quality of forage available to them in the snow-free season were conducted in 1970 and 1975, 15 and 20 years after logging. Results showed that deer fecal counts and forage production were greater on clearcut than on uncut strips, but that inherent forage quality as indexed by crude protein content and digestibility was not different between the two treatments (Wallmo et al. 1972, Regelin et al. 1974, Regelin and Wallmo 1978).

The study reported here was conducted in a nearby watershed to describe the initial responses of selected herbivores and understory plant production to a different water enhancement cutting practice than was applied at Fool Creek.

STUDY AREA

The study was conducted on a south-facing segment of the 667-acre Deadhorse Creek Watershed on the Fraser Experimental Forest. Elevations average about 10,000 feet, and slopes range from gentle to greater than 70%. Soils are gravelly, sandy loams with low erodability (Retzer 1962). Winters are long, cold, and snowy, and summers are cool and moist. Annual temperatures averaged about 32°F, and precipitation 25.6 ± 3.7 inches at the on-site Deadhorse gauging station during the 7-year study period. About two-thirds of the annual precipitation falls as snow from October through May.[2]

The experiment on which this study was superimposed utilized a current "state-of-the-art" cutting practice for maximizing water production. It consisted of monitoring snow depths and water leaving the site before and after clearcutting 12, more or less evenly-spaced, 3-acre circular patches (r = 204 feet) in a 101-acre segment of the Deadhorse Watershed (Troendle 1983) (fig. 1).

Overstory vegetation consisted of mature to overmature Engelmann spruce (*Picea engelmannii*),[3] subalpine fir (*Abies lasiocarpa*), and lodgepole pine (*Pinus contorta*). A few large, old Douglas-fir (*Pseudotsuga menziesii*) also were present. Understory vegetation on most of the Watershed was low-growing, and dominated by *Vaccinium scoparium* with lesser amounts of *V. myrtillus*, a few other low shrubs, and very sparse scattering of sedges and forbs. This vegetation corresponds closely to the *Abies lasiocarpa/Vaccinium scoparium* plant association that has been widely de-

[2]*Data on file at the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.*

[3]*Plant nomenclature generally corresponds with Harrington (1954).*

Figure 1.—Distribution of 3-acre circular clearcuts designed to augment streamflow on Deadhorse Creek in central Colorado.

scribed in the northern and central Rockies (Hoffman and Alexander 1976, 1980, 1983).

A small, more moist, and subsequently highly important part of the area was occupied by vegetation resembling that described as an *Abies lasiocarpa/Picea engelmannii/Senecio triangularis* plant association (Hess 1981). Although the stand was aged, it was more or less intact, with relatively little dead wood on the ground.

The Watershed serves as spring, summer, and fall habitat for mule deer and elk (*Cervus elaphus canadensis*) and various bird species, and as year-round habitat for many resident species, such as blue grouse (*Dendrogapus obscurus*), gray jays (*Perisoreus canadensis*), and mountain chickadees (*Parus gambeli*) (Scott et al. 1982) and pine marten (*Martes americana*), snowshoe hare (*Lepus americanus*), and golden mantled squirrels (*Spermophilus lateralis*) (Alexander and Watkins 1977).

Scott et al. (1978) described the snag component of the study area before logging, and the response of birds and small mammals to clearcutting shortly after logging (Scott et al. 1982).

METHODS

The area was logged in 1977. Merchantable material was transported to roads by rubber-tired skidders, except on the steepest slopes where crawler tractors were used. About 10,000 fbm/acre were hauled to the mill. During logging, all live trees greater than 4 inches d.b.h. were felled. Slash was scattered, and steeper skid-trails were seeded with grasses to control erosion. Species seeded included *Melilotus alba* and *M. officinalis*, *Agropyron intermedium*, and *Lolium perenne*, each at 15%, and *Bromus inermis*, *Agropyron trachycaulum*, *Phleum* sp., and *Poa pratensis*, each at 10% of the total mixture. Seeding rates were unknown; but, relatively little of the clearcut area was seeded.

For this study, four blocks judged to be typical of those to be clearcut were paired with four adjacent uncut sites. The four patches to be logged are subsequently referred to as "average" sites. In addition, a fifth block, on a much wetter site, and also scheduled for logging, was selected for study. However, there was no comparable uncut wet site to serve as a control.

Moist sites occur on small benches and are watered by springs or seeps, or occasionally by shallow drainages. Logging operations may greatly widen the drainage, or may increase the area influenced by the spring, and thereby create larger, well- or excessively-watered areas. Overstory removal upslope, or on the moist sites themselves, also may increase amounts of water available for understory plant growth.

Observations prior to the study indicated that sites available for controls within the study area had similar species composition, but greater amounts of understory vegetation than the blocks marked for clearcutting. Consequently, direct comparisions between responses

on clearcuts and controls were not appropriate. Therefore, comparisons were made separately within the clearcut and uncut components; and effects of logging on the attributes measured are inferred where annual and periodic changes occurred on clearcut but not on uncut blocks.

Inventories of the vegetative component and herbivore activity were conducted on the same grid. All data were collected on three parallel, 275-foot lines located about 100 feet apart, with the center line passing near each block center. Lines were oriented parallel to slopes and began and ended about 50 feet from block edges. Lines were permanently marked with wooden stakes at 55-foot intervals. Thus, a total of 15 staked points, 5 on each line, were established on each block. Except for overstory measurements and fecal counts, plot stakes were used only to orient sampling each year.

Prelogging stand characteristics were determined from 4-milacre circular plots centered at each wooden stake in each block. Within each plot, trees were counted by species, and their diameters (d.b.h.) were measured. Logging slash expressed as percent cover was estimated each year after logging, during understory plant inventories.

Plant Production and Ground Cover

Plant production was determined by clipping current growth to a 5-foot height, within ten, 1-foot quadrats spaced equally along each sampling line. Woody plants, graminoids, and forbs were sacked separately, were weighed green in the field, and later were oven-dried at 55°C to determine moisture content. In addition, samples of *Vaccinium* spp., *Carex rossii*, and *Arnica cordifolia*, the most common shrub, graminoid, and forb on uncut and clearcut blocks, were collected 3 and 5 years after logging to help to interpret forage quality data.

Plant cover by species was estimated by 10% increments in fifty, 1- by 2-inch rated microplots spaced about 5 feet apart on each line (Morris 1973). Logging slash was similarly inventoried during plant sampling.

Production and cover were measured near the peak of each growing season, during the second or third week of August each year from 1976, the year before logging, through 1982, the fifth year after logging was completed.

Effects of the clearcutting on the quality of understory vegetation as potential forage were evaluated after clearcutting by comparing moisture, crude protein content, and dry matter digestibility using analytic procedures similar to those used by Regelin et al. (1974). Rumen inoculum from a domestic cow, fed grass hay, was used in digestibility determinations.

Herbivore Activity

Elk, deer, and snowshoe hare activity was monitored in the fall each year from pellet group counts made on five, 8- x 55-foot segments on the two outside sampling lines in each block.

Data Analysis

Analysis of variance ($P = 0.05$) was used to test for annual and periodic differences for all measured attributes. Tukey's test was used to separate means where appropriate (Snedecor 1961). Linear regression ($P = 0.05$) was used to test for significance of time-trends after clearcutting. The quantitative statements greater or lesser, increases or decreases, etc., used in the following sections indicate that values reported are significantly different, or that time-trend relationships are significant ($P = 0.05$).

RESULTS

Prelogging overstory characteristics, including the contributions of each tree species to the total component, are shown in table 1. As expected, logging reduced numbers and basal areas of trees dramatically in the clearcut blocks. However, there was sufficient advanced regeneration remaining—more than 300 seedlings and saplings per acre—to adequately stock the clearcut blocks after logging. Tables 2, 3, and 4 show cover of slash before and after logging. Amounts within clearcut blocks ranged from none to heavy, depending on location, and averaged 20% cover during the 5-year post-logging period.

The small gain in slash on uncut blocks resulted from blowdown, probably triggered by clearcutting in the nearby logged sites. Skidding on the moist site caused somewhat boggy conditions over much of that block.

Plant Production

Average Sites

Before logging, the bulk of understory biomass was produced by the woody plant component on both the uncut blocks and those to be clearcut. The same pattern

Table 1.—Prelogging overstory characteristics on uncut and clearcut blocks in a subalpine forest in central Colorado.

	Engelmann spruce	Subalpine fir	Lodgepole pine	All species[1]
		Number per acre		
		≥4.0 inches d.b.h.		
Uncut	46	183	79	308 ± 71
Clearcuts				
Average	104	104	108	316 ± 73
Moist	117	100	17	234 ± 82
		Basal area (ft²/acre)		
Uncut	27.9	51.8	43.1	122.8 ± 38.5
Clearcuts				
Average	48.8	26.7	71.3	146.8 ± 41
Moist	102.9	32.2	2.7	137.8 ± 80.0

[1] *Confidence intervals* = $\bar{X} \pm t.05\,(S\bar{X})$.

Table 2.—Percent understory cover on uncut controls adjacent to average clearcut blocks in a subalpine forest in central Colorado.

Growth form and species	Before logging (1976)	Years after logging (1978-82) 1	2	3	4	5	Before versus after logging[1]	
Woody plants								
Vaccinium spp.	32.4	34.0	36.4	31.0	30.7	35.7	32.4a	33.6a
Pachystima myrsinites	3.6	3.8	2.9	4.8	3.9	3.6	3.6a	3.8a
Shepherdia canadensis	3.0	3.5	2.7	4.4	3.8	3.1	3.0a	3.5a
Juniperus communis	0.9	1.2	1.8	0.9	1.4	1.9	0.9a	1.4a
Abies lasiocarpa	0.8	1.0	1.0	0.5	0.5	1.0	0.8a	0.8a
Arctostaphylos uva-ursi	0.6	0.2	0.3	1.0	0.6	0.6	0.6a	0.5a
Rosa sp.	0.5	0.8	1.5	1.9	0.9	0.7	0.5a	1.2a
Pinus contorta	0.3	0.6	0.5	0.7	0.3	0.4	0.3a	0.5a
Berberis repens	0.2	0.4	0.2	0.4	0.5	0.6	0.2a	0.4a
All woody plants[2]	42.3a	45.5a	47.3a	45.6a	42.6a	47.6a	42.3a	45.7a
Graminoids								
Carex spp.	0.6	0.7	1.1	1.3	0.8	1.4	0.6a	1.1a
All graminoids[2]	0.7a	0.7a	1.1a	1.3a	0.8a	1.4a	0.7a	1.1a
Forbs								
Arnica cordifolia	4.3	3.3	4.2	4.8	3.3	4.8	4.3a	4.1a
Happlopapus parryi	0.7	0.8	1.7	1.3	0.8	1.1	0.7a	1.1a
Senecio crassulus	0.4	0.5	0.3	0.1	0.3	0.6	0.4a	0.4a
Cirsium sp.	0.2	0.1	0.4	1.3	0.6	0.9	0.2a	0.7a
Fragaria ovatum	0.2	0.1	0.6	0.3	0.3	0.4	0.2a	0.3a
Epilobium angustifolium	0.1	0.1	0.0	0.2	0.2	0.2	0.1a	0.1a
Geranium richardsonii	0.1	0.3	0.5	0.3	0.1	0.1	0.1a	0.3a
Pedicularis racemosa	0.1	0.1	0.3	0.4	0.7	0.5	0.1a	0.4a
Pyrola sp.	0.1	0.1	0.0	0.1	0.0	0.1	0.1a	0.1a
Others	1.0	1.0	0.7	0.6	0.5	0.7	1.0a	0.7a
All forbs[2]	7.2a	6.4a	8.7a	9.4a	6.8a	9.4a	7.2a	8.2a
Total plant cover[2]	50.2a	52.6a	57.1a	56.3a	50.2a	58.4a	50.2a	54.9a
Slash[2]	2.7a	3.0a	5.1a	6.6a	5.3a	5.7a	3.1a	5.1b

[1]*Within species, before and the mean value after clearcutting followed by the same letter are not significantly different (P = 0.05).*
[2]*Among years, means followed by the same letter are not significantly different (P = 0.05).*

Table 3.—Percent understory cover before and after clearcutting average blocks in a subalpine forest in central Colorado.

Growth form and species	Before logging (1976)	Years after logging (1978-82) 1	2	3	4	5	Before versus after logging[1]	
Woody plants								
Vaccinium spp.	17.2	12.6	18.3	18.8	14.7	22.4	17.2a	17.4a
Shepherdia canadensis	1.0	0.9	0.8	0.6	0.8	1.4	1.0a	0.9a
Pachystima myrsinites	0.7	1.7	3.0	2.8	3.4	3.4	0.7a	2.9b
Abies lasiocarpa	0.4	0.4	0.8	0.3	0.4	0.5	0.4a	0.5a
Arctostaphylos uva-ursi[3]	0.3	0.1	0.6	0.7	1.2	1.9	0.3a	0.9b
Rosa sp.[3]	0.3	0.3	1.6	2.3	2.2	2.8	0.3a	1.8b
Juniperus communis	0.2	0.2	0.8	1.4	0.8	0.6	0.2a	0.8a
Berberis repens	0.2	0.1	0.1	0.1	0.2	0.2	0.2a	0.1a
All woody plants[2]	20.3bc	16.3c	26.0b	27.0b	23.7bc	33.2a	20.3a	25.3b
Graminoids								
Carex spp.[3]	0.2	0.3	1.0	5.3	9.8	14.1	0.2a	6.1b
Seeded grasses[3,4]	0.0	0.1	0.5	0.8	1.9	2.3	0.0a	1.1b
All graminoids[2,4]	0.2c	0.4c	1.5c	6.1bc	11.7ab	16.4a	0.2a	7.2b
Forbs								
Arnica cordifolia[3]	0.3	1.4	3.1	4.0	4.6	5.0	0.3a	3.6b
Happlopapus parryi[3]	0.2	0.2	0.2	0.3	0.8	0.8	0.2a	0.5a
Senecio crassulus	0.1	0.2	0.2	< 0.1	0.2	0.1	0.1a	0.1a
Epilobium angustifolium[3]	0.1	0.1	0.3	0.7	1.1	1.9	0.1a	0.8b
Cirsium sp.	0.0	0.0	0.0	0.0	0.1	0.4	0.0a	0.1a
Taraxacum officinale	0.0	0.0	0.3	0.2	0.9	1.0	0.0a	0.5b
Others	0.2	0.1	0.1	0.9	0.2	1.0	0.2a	0.5b
All forbs[3]	0.9c[2]	2.0c	4.2bc	6.1b	7.9ab	10.2a	0.9a	6.1b
All forms and species[3]	21.4d[2]	18.7d	31.7c	39.2bc	43.3b	59.8a	21.4a	38.5b
Slash[2]	2.0b	18.1a	20.2a	22.3a	20.8a	18.6a	2.0a	20.0b

[1]*Within species, before and the mean value after clearcutting followed by the same letter are not significantly different (P = 0.05).*
[2]*Among years, means followed by the same letter are not significantly different (P = 0.05).*
[3]*Cover is significantly correlated with years after logging (P = 0.05).*
[4]*From the erosion control seeding, only* Agropyron intermedium, Bromus inermis, *and* Phleum *spp. were encountered during plant inventories.*

Table 4.—Percent understory cover before and after clearcutting a moist site in a subalpine forest in central Colorado.[1]

Growth form and species	Before logging (1976)	Years after logging (1978–82)					Before versus after logging[2]	
		1	2	3	4	5		
Woody plants								
Vaccinium spp.	3.3	1.1	0.3	3.7	0.6	0.3	3.3a	1.2b
Rosa sp.	1.7	1.6	1.7	1.3	1.2	1.1	1.7a	1.4a
Ribes lacustre	1.3	1.0	2.3	2.0	1.0	2.2	1.3a	1.7a
Others[4]	1.5	1.6	1.3	0.5	0.0	0.0	1.5a	0.7b
All woody plants[3]	7.8a	5.3a	5.6a	7.5a	2.8a	3.6a	7.8a	5.0b
Graminoids								
Carex spp.	4.9	5.5	5.6	8.5	8.2	6.8	4.9a	6.9a
Bromus ciliatus	2.9	3.3	1.0	1.6	2.5	1.5	2.9a	2.0a
Calamagrostis canadensis[4]	0.2	0.3	4.2	4.1	4.2	10.9	0.2a	4.7b
Luzula parviflora[4]	0.1	0.2	0.0	0.8	2.9	6.7	0.1a	2.1b
Other native graminoids	0.0	0.7	0.0	0.0	0.0	0.0	0.0a	0.1a
Seeded grasses[4]	0.0	0.8	7.7	12.9	14.5	12.6	0.0a	9.7b
All graminoids[3,4]	8.1b	10.1b	18.5ab	27.9ab	32.3ab	38.5a	8.1a	25.5b
Forbs								
Geranium richardsonii	5.1	3.9	4.2	3.7	3.2	7.5	5.1a	4.5a
Arnica cordifolia	4.0	2.6	5.1	6.9	2.7	4.4	4.0a	4.3a
Pyrola sp.	2.7	0.8	5.7	3.9	1.4	2.3	2.7a	2.8a
Mertensia ciliata[4]	2.7	3.4	3.6	4.9	13.7	10.7	2.7a	7.3b
Smilacina stellata[4]	1.7	1.4	0.6	0.6	<.1	0.0	1.7a	0.5b
Senecio triangularis[4]	1.6	0.0	3.4	6.8	5.0	10.7	1.6a	5.2b
Erigeron sp.	1.1	1.1	0.9	0.0	2.3	2.7	1.1a	1.4a
Aconitum columbianum	0.9	3.4	3.2	3.5	3.1	5.7	0.9a	3.8b
Ligusticum porteri[4]	0.9	0.3	0.3	0.3	1.3	1.5	0.9a	0.7a
Equisetum arvense	0.7	6.7	21.5	18.1	17.0	30.9	2.0a	18.8b
Heracleum lanatum[4]	0.6	3.1	8.2	8.9	13.3	10.7	0.6a	8.8b
Cardamine cordifolia	0.6	0.7	0.7	4.4	4.3	6.1	0.6a	3.2b
Taraxacum officinale[4]	0.3	0.3	0.3	<0.1	0.5	0.4	0.3a	0.3a
Epilobium angustifolium	0.3	0.0	1.2	3.1	2.5	2.8	0.3a	1.9a
Others	7.6	0.0	1.9	0.0	7.6	7.0	3.6a	3.3a
All forbs[3,4]	30.8c	27.7c	60.8bc	65.1bc	77.9ab	103.4a	30.8a	66.9b
All forms and species[3,4]	46.7c	43.1c	84.9bc	100.5ab	113.0ab	145.5a	46.7a	97.4b
Slash[2]	3.0b	19.4a	18.6a	18.8a	17.6a	18.4a	3.0a	18.6b

[1] *No suitable mesic uncut block was available for comparison.*
[2] *Within species, before and the mean value after clearcutting followed by the same letter are not significantly different (P = 0.05).*
[3] *Among years, means followed by the same letter are not significantly different (P = 0.05).*
[4] *Cover is significantly correlated with years after logging (P = 0.05).*

persisted after logging although, as stated earlier, the uncut controls were more heavily vegetated than the areas to be logged (fig. 2). Table 5 shows that amounts of woody plants on the uncut blocks were similar through the study period, but that their production increased after logging on the clearcut sites.

Graminoids consisted of very small amounts of sedges on both uncut and clearcut blocks in the year prior to logging; a similar postlogging pattern persisted on the uncut controls. On clearcut blocks, graminoid production increased more or less consistently each year after logging, resulting primarily from greater amounts of sedges, but also from grasses seeded for erosion control (table 5).

Forb production was somewhat erratic from year-to-year on uncut blocks, but showed no overall change during the investigation (table 5). More forbs were produced on clearcuts after logging than before.

Among all growth forms, plant production was unchanged on uncut blocks, but increased markedly in the years after logging on the clearcut sites.

Moist Clearcut Site

Before logging, the moist site supported relatively few woody plants, but many species of graminoids and forbs. Plant production was also much greater before logging than on the average clearcuts (table 5). Woody plant production declined abruptly after logging and did not recover, whereas graminoids and forbs increased dramatically and consistently after clearcutting (fig. 3).

Ground Cover

Average Sites

Among all growth forms, plant cover was unchanged on uncut blocks, but increased after logging on those that were clearcut. Woody plants comprised the dominant growth form on all blocks before and after logging (tables 2 and 3). These plants made up 90% and 95%, respectively, of the understory cover on both clearcut

Figure 2.—Surface of an average clearcut block in the fourth year after logging on Deadhorse Creek in central Colorado. Plant cover, mostly shrubs, totalled about 43%.

Table 5.—Dry weight understory plant production (pounds/acre) on uncut and clearcut blocks in a subalpine forest in central Colorado.

Growth form and treatment	Before logging (1976)	Years after logging (1978–82)[1]					Before versus after logging[2]	
		1	2	3	4	5		
Woody plants								
Uncut	373a	484a	462a	392a	353a	416a	373a	421a
Clearcut								
Average	223b	242b	270b	314b	228b	447a	223a	300b
Moist	130a	32a	29a	46a	74a	14a	130a	39b
Graminoids								
Uncut	<1a	1a	4a	7a	1a	1a	<1a	3a
Clearcut								
Average[3,4]	1b	1b	9b	25b	98ab	136a	1a	54b
Moist[3,4]	137bc	46c	451bc	339bc	928ab	1,416a	137a	636b
Forbs								
Uncut	10a	15a	21a	22a	17a	33a	10a	22a
Clearcut								
Average[4]	1c	8bc	46b	45b	34bc	90a	1a	45b
Moist[4]	355b	106b	387b	1,254ab	1,181ab	1,865a	355a	959b
Totals								
Uncut	384a	500a	487a	421a	371a	450a	384a	446a
Clearcut								
Average[4]	225d	251cd	325bc	384b	360bc	673a	225a	399b
Moist[4]	622c	184c	867bc	1,639b	2,183b	3,295a	622a	1,634b

[1] *Within growth forms and treatments, means followed by the same letter are not significantly different (P = 0.05).*

[2] *Within growth forms and treatments, before and the mean value after clearcutting followed by the same letter are not significantly different (P = 0.05).*

[3] *Includes grasses seeded for erosion control.*

[4] *Production is signiticantly correlated with years after logging (P = 0.05).*

Figure 3.—Surface of the moist clearcut block in the fourth year after logging on Deadhorse Creek in central Colorado. Plant cover, mostly herbaceous species, totaled more than 100%.

and control blocks. Neither total woody cover nor cover of any of the species observed changed during the study on uncut blocks (table 2). Total woody cover and that of several individual species increased on clearcut blocks after logging.

Very small amounts of cover of two grass species and two sedges were found during the study on uncut blocks (tables 2 and 6). On clearcuts, however, cover of graminoids increased markedly after logging, with sedges and seeded grass comprising virtually all of the increase (table 3).

On uncut blocks, total cover of forbs and that of the common forb species were not different through the study period, whereas total forb cover, and that of four of the six species monitored, was greater after logging on the clearcut sites. *Arnica cordifolia* was the major increaser.

Logging had little effect on the presence or absence of individual plant species (table 6). Eleven woody species were found before and after logging on both clearcut and uncut blocks. Only four graminoids were documented during the study on uncut blocks. The same four species were present prior to logging on the clearcut sites; only one additional sedge, plus three grass species seeded for erosion control were listed after logging.

The same 10 forbs were present before clearcutting on all blocks (table 6). After logging, two additional forbs were found on both uncut and clearcut sites. Only one species, *Pedicularis racemosa*, was present before, and absent after logging on the clearcut blocks.

Moist Clearcut Site

A decline in the inherent low cover of woody plants followed clearcutting on the moist site (table 4). Herbaceous plants however, showed a three-fold gain in cover. Graminoids, especially *Calamagrostis canadensis*, and grasses seeded for erosion control were major contributors to the increase.

Forbs also showed marked increases in cover. Seven of the 15 forb species evaluated had greater cover after, than before logging. Largest gains were exhibited by *Mertensia ciliata, Senecio triangularis, Equisetum arvense, Heracleum lanatum,* and *Cardamine cordifolia.* All of these species are moist-site indicators in subalpine forests.

A total of 39 species was recorded before logging on the moist site (table 6). Four additional species were found after logging; three of these were grasses seeded for erosion control.

Table 6.—Plant species present (+) on uncut and before and after logging on clearcut blocks in a subalpine forest in central Colorado.

Growth form and species	Clearcut sites				Uncut sites	
	Average		Moist			
	Before	After	Before	After	Before	After
Woody plants						
Abies lasiocarpa	+	+	+	+	+	+
Arctostaphylos uva-ursi	+	+	+	+	+	+
Berberis repens	+	+			+	+
Juniperus communis	+	+			+	+
Lonicera involucrata			+	+		
Pachystima myrsinites	+	+	+	+	+	+
Pinus contorta	+	+			+	+
Picea engelmannii	+	+			+	+
Ribes lacustre	+	+	+	+	+	+
Rosa sp.	+	+	+	+	+	+
Shepherdia canadensis	+	+			+	+
Vaccinium spp.	+	+	+	+	+	+
Graminoids						
Agropyron intermedium[1]		+		+		
Bromus ciliatus	+	+	+	+	+	+
B. inermis[1]		+		+		
Calamagrostis canadensis			+	+		
Carex foena		+	+	+		
C. geyeri	+	+	+	+	+	+
C. rossii	+	+	+	+	+	+
Elymus glaucus			+	+		
Juncus balticus			+	+		
Luzula parviflora			+	+		
Melica bulbosa			+	+		
Phleum sp.[1]		+		+		
Poa pratensis	+	+	+	+	+	+
Forbs						
Aconitum columbianum			+	+		
Arnica cordifolia	+	+	+	+	+	+
Cardamine cordifolia			+	+		
Cirsium sp.		+	+	+		
Epilobium angustifolium	+	+		+	+	+
Equisetum arvense			+	+		
Erigeron sp.	+	+	+	+		
Fragaria ovalis	+	+	+	+	+	+
Geranium richardsonii	+	+	+	+	+	+
Haplopappus parryi	+	+			+	+
Heracleum lanatum			+	+		
Galium boreale			+	+		
Ligusticum porteri			+	+		
Mitella stauropetala			+	+		
Mertensia ciliata			+	+		
Osmorhiza obtusa			+	+		
Pedicularis racemosa	+				+	+
Pyrola sp.	+	+	+	+	+	+
Saxifraga arguta			+	+		
Senecio amplectens	+	+	+	+	+	+
S. crassulus	+	+	+	+	+	+
S. triangularis			+	+		
Smilacina stellata			+	+		
Solidago decumbens	+	+			+	+
Taraxacum officinale		+	+	+		
Veratrum californicum			+	+		

[1]*Grasses seeded for erosion control.*

Forage Quality

Average Sites

Moisture content of understory samples was unchanged over the postlogging period on the uncut blocks, averaging about 60% for the 5-year span (table 7). In vegetation from the clearcuts, moisture content gradually increased and was greater after 5 years, because the samples contained larger proportions of forbs which contained high amounts of moisture (tables 5 and 7).

Crude protein content was unchanged on uncut blocks, averaging 9.2% over the study period (table 7). On clearcuts, the understory contained less crude protein in the year after logging but was unchanged thereafter, averaging 10.4% annually.

Table 7.—Characteristics of understory vegetation on uncut and clearcut blocks in a subalpine forest in central Colorado.

Characteristics and treatments	Years after logging (1978–1982)[1]					5-year mean
	1	2	3	4	5	
Moisture (percent)						
Uncut	56.8b	59.3a	59.2a	59.0a	59.8a	58.8
Clearcut						
Average[2]	57.0b	58.0ab	59.7ab	60.5ab	62.3a	59.5
Moist[2]	62.3a	64.5a	74.4b	73.3b	76.3b	70.1
Crude protein (percent)						
Uncut	8.6a	9.2a	9.1a	9.1a	9.8a	9.2
Clearcut						
Average	8.2b	10.2ab	11.1a	11.4a	11.1a	10.4
Moist	10,8ab	8.2e	9.8bc	9.3cd	11.8a	10.0
In vitro digestibility (percent)						
Uncut	33.2bc	29.0c	32.5bc	35.7b	41.3a	34.3
Clearcut						
Average[2]	33.9c	33.0c	36.9bc	43.4b	51.3a	39.7
Moist	63.8a	64.9a	68.4a	65.1a	65.1a	65.5
Crude protein (pounds per acre, dry weight)						
Uncut	43a	44a	38a	33a	46a	41
Clearcut						
Average[2]	21b	34ab	43ab	41ab	68a	41
Moist[2]	20d	71cd	161bc	203b	389a	169

[1] *Within characteristics and treatments, means followed by the same letter are not significantly different (P = 0.05).*

[2] *Values are significantly correlated with years after logging (P = 0.05).*

Total amounts of crude protein available to herbivores are shown in table 7. These values were determined by multiplying annual understory production by its crude protein content. Amounts available on uncut blocks were similar over the postlogging period, averaging about 41 pounds/acre. Although crude protein availability increased after logging on the clearcuts, amounts available averaged only 41 pounds/acre, the same as on uncut blocks, because plant production was inherently lower than on the uncut sites.

In vitro digestibility of understory vegetation increased during the study on uncut and clearcut blocks, averaging 34% and 40%, respectively (table 7). The higher values on uncut sites were attributed to higher proportions of highly digestible forbs in the uncut understory and to more forbs, and equally highly digestible graminoids in the years after logging on the clearcut blocks (tables 5, 7, and 8).

Moist Clearcut Site

Moisture content of the understory vegetation increased after the moist site was clearcut (table 7). Gains in moisture content were attributed to steadily increasing proportions of native and seeded grasses, and forbs in the understory component (tables 4, 5, and 8).

Crude protein content was high in the year after logging, declined the following year, and then gradually increased again through the final 3 years (table 7). No reasons for this pattern were evident.

Crude protein availability increased dramatically during the years after clearcutting the moist site (table 7). Virtually all of the gains can be attributed to increases in total amounts of vegetation produced, rather than changes in proportions of the various growth forms in the samples.

In vitro digestibility was constant during the study, probably because relative amounts of highly digestible graminoids and forbs were already large by the first year after logging (tables 4, 5, and 7).

Herbivore Activity

Average Sites

Numbers of herbivore fecal groups were low before and after logging on both uncut and clearcut blocks (table 9). Also, there were no differences in numbers of elk groups before and after clearcutting on either set of blocks, although numbers increased gradually on the clearcut sites. Numbers of deer droppings, however, increased over the postlogging period on both areas, although numbers were still low. Hare activity, as indexed by frequency of plots occupied by fecal pellets, was lower after clearcutting but unchanged on uncut blocks.

Moist Clearcut Site

Elk and deer pellet groups were both more abundant after than before logging. Hare activity decreased after clearcutting (table 9).

Table 8.—Characteristics of three understory plants on uncut and clearcut blocks in a subalpine forest in central Colorado.[1]

Characteristic	*Vaccinium* spp.		*Carex rossii*		*Arnica cordifolia*	
	Years after logging (1978-82)					
	3	5	3	5	3	5
Moisture (percent)						
Uncut	57.3 ± 6.3	60.2 ± 1.5	54.3 ± 5.8	59.6 ± 5.6	80.0 ± 3.9	81.6 ± 4.2
Clearcut						
Average	60.3 ± 8.9	60.4 ± 2.5	58.9 ± 8.7	60.4 ± 2.6	77.7 ± 11.0	79.0 ± 3.1
Moist[2]	61.1	65.8	59.4	64.3	70.1	72.0
Crude protein (percent)						
Uncut	9.3 ± 1.0	11.0 ± 1.5	9.9 ± 3.7	10.4 ± 4.2	8.3 ± 2.0	9.4 ± 1.4
Clearcut						
Average	11.2 ± 1.9	12.6 ± 0.8	12.6 ± 2.2	10.9 ± 1.3	10.5 ± 1.0	11.1 ± 0.8
Moist[2]	11.8	12.6	13.9	12.5	12.6	13.5
In vitro digestibility (percent)						
Uncut	28.0 ± 3.4	31.1 ± 5.6	54.9 ± 6.0	62.7 ± 5.1	70.8 ± 5.8	77.5 ± 5.5
Clearcut						
Average	29.2 ± 3.2	38.3 ± 4.7	61.4 ± 1.6	61.3 ± 1.5	70.0 ± 5.4	72.1 ± 9.6
Moist[2]	27.1	32.9	62.2	62.1	68.4	65.4

[1]*Confidence intervals equal* $\bar{X} \pm t\ .05\ (S\bar{X})$.
[2]*Confidence intervals could not be calculated because values were obtained from single samples.*

Table 9.—Herbivore fecal groups on uncut and clearcut blocks in a subalpine forest in central Colorado.

Herbivore[1]	Before logging (1976)	Years after logging (1978-82)					Before versus after logging[2]	
		1	2	3	4	5		
	Number per acre							
Elk								
Uncut	23a	33a	18a	20a	28a	18a	23a	23a
Clearcut								
Average[3]	18ab	3a	0a	15a	28a	38b	18a	17a
Moist	30b	0b	110ab	70ab	90ab	120a	30a	78b
Deer								
Uncut[3]	13a	18ab	15ab	18ab	35ab	55b	13a	28b
Clearcut								
Average[3]	18a	5a	15a	40a	60ab	95b	18a	43b
Moist[3]	30c	10c	40bc	70abc	90ab	110a	30a	64b
	Frequency of occurrence in 0.1-acre plots							
Snowshoe hare								
Uncut	48a	60a	50a	35a	50a	50a	48a	49a
Clearcut								
Average	35a	8b	15b	3b	15b	38a	35a	16b
Moist	70a	70a	50a	0b	20b	0b	70a	28b

[1]*Within herbivores and treatments, means followed by the same letter are not significantly different (P = 0.05).*
[2]*Within herbivores and treatments, before and the mean value after clearcutting followed by the same letter are not significantly different (P = 0.05).*
[3]*Numbers or frequencies are significantly correlated with years after logging (P = 0.05).*

DISCUSSION

Logging on the clearcut blocks produced moderately large amounts of slash, which inhibited to some extent space availability for the growth of understory vegetation. In addition, many of the snags inventoried by Scott et al. (1978) were toppled by wind during the 5 years following logging, adding to the slash loading. Concentrations of slash also restricted accessibility to deer and elk on some parts of the clearcuts but probably had little effect on use by these animals. Studies in the western states and Canada have documented increases in understory production following partial or complete removal of tree overstories (Ffolliott and Clary 1982). Few, however, have concerned subalpine forests in the central Rockies, or long-term monitoring after clearcutting. Reynolds (1962) found that production peaked 6 years after logging ponderosa pine (*Pinus ponderosa*) in northern Arizona and declined to pretreatment levels after 15 years. Maximum understory development occurred at

11 years in clearcut and burned lodgepole pine in Montana (Basile 1975). Understory production (Wallmo et al. 1972) on Fool Creek 15 years after logging (853 pounds/acre) was still being sustained by the 20th year (759 pounds/acre) (Regelin and Wallmo 1978). Amounts of understory vegetation on comparable uncut sites were also similar (391 and 433 pounds/acre).

Production on average clearcuts had not reached these levels by the fifth year after logging, although an upward trend was evident at that time. Production on uncut blocks over the 5-year postlogging period was comparable to the 15- and 20-year levels on Fool Creek (table 5) (Regelin and Wallmo 1978). No data were obtained until 15 years after logging on Fool Creek; therefore, no estimates can be made as to the year(s) of peak production, or if production was declining at those times.

Whether plant production on the Deadhorse Creek clearcuts will continue to increase is uncertain. Cursory examination of data from 1983, the sixth year after logging, suggests that production that year, on average clearcuts, was about 40% lower than in the highly productive fifth year; but, this may be merely a result of good growing conditions one year, and poor conditions the next year.

Plant production and the variety of species before logging on the moist site far exceeded that on the uncut, or the average blocks. The same pattern was even more evident after clearcutting. The value of a moist environment in a subalpine forest ecosystem for production of potential big game forage was evident.

Virtually all plant species encountered were perennials. Woody plants were well represented in numbers of species and cover on the average clearcut and the uncut blocks. Graminoids and forbs, however, were relatively scarce on both areas, especially when compared with the moist site or Fool Creek (Wallmo et al. 1972).

Except for contributions from seeded grasses, increases in plant cover after clearcutting resulted almost exclusively from greater abundance of species present before logging, rather than from natural seeding from outside the study area. In fact, among all study sites, no native species was found after logging that had not been present before treatment. Similarly, no species present before logging was absent afterward (table 6).

Nearly all of the plant species observed are among those found to be eaten by deer on Fool Creek (Wallmo et al. 1972). According to studies elsewhere, many are also eaten by elk (Kufeld 1973, Thomas and Toweill 1982). Although *Vaccinium* spp. rated high in preference as deer forage on Fool Creek, its abundance was little affected by logging on the Deadhorse Creek area. Moreover, except for seeded grasses and the multispecies abundance on the moist site, there appeared to be little quantitative gain in availability of forage during the first 5 years after logging.

Changes in plant characteristics related to forage quality suggest that clearcutting was potentially beneficial. Moisture content, crude protein, and in vitro digestibility of understory vegetation increased through the study period on clearcuts, but was unchanged on uncut blocks.

Although widely distributed throughout the Fraser Experimental Forest during the spring, summer, and fall, elk and deer populations are small, as might be expected in this closed-canopy subalpine forest (Porter 1959, Wallmo 1969). No game trails were observed on the study area before or after logging. The relatively small acreage clearcut on Deadhorse Creek was not expected to radically change distribution patterns, or intensities of activity of these animals.

Although others, including Collins and Urness (1981) have demonstrated shortcomings of pellet group counts as indicators of elk and deer habitat usage, it is believed that they provide valid and useful information for the purposes reported here. Elk activity was unchanged on uncut and average clearcut sites before and after logging, but increased measurably on the moist site after clearcutting. Deer activity was greater after logging on uncut and all clearcut blocks.

The decline of snowshoe hare activity through 5 years after clearcutting was predictable, because these animals are known to favor more heavily vegetated habitats (Wolfe et al. 1982).

Effects of the logging on many other, small, nongame wildlife species appeared negligible (Scott et al. 1982).

CONCLUSIONS

Clearcutting in small blocks on a relatively dry site resulted in few major changes in understory vegetation and herbivore activity during 5 years after treatment. Logging a single moist site in this forest produced dramatic increases in plant production, species cover, and resulted in increased big game activity. Regelin and Wallmo (1978) showed that forage production was greater on clearcut than on uncut strips 20 years after logging on the nearby Fool Creek Watershed. Because trees grow slowly in central Colorado subalpine forests, the increases in forage availability observed over 5 years on the Deadhorse Creek blocks can be expected to persist at least as long as they have on Fool Creek.

Overall effects of this cutting pattern—the first entry into an extensive mature forest—on the wildlife species encountered and their habitats appeared negligible, except for the possible impact on species such as cavity-nesters, which require mature forest habitats. The potential for such adverse effects would be important only if prelogging habitats were fully occupied and no adjacent space was available for these species.

A second near-term entry into the same watershed potentially could have much more dramatic effects. Removing another 35% of the overstory by clearcutting would leave only about 30% of the area in mature forest, and might produce substantial on-site declines in wildlife species requiring such habitats, and increasing numbers of those favored by earlier successional stages. Big game forage would be increased; but, cover for them would be reduced. Closed-canopy dwellers also would be adversely affected as more mature timber is logged.

Similar changes, however, are likely whether the present forest is logged in any pattern, or regenerates naturally. The difference will be in the concentration of intensive activity required for logging compared with that occurring in the relatively imperceptible long-term natural succession.

However, the replacement of the old forest by catastrophic change, such as fire or insect infestation, could disrupt far more acreage in a short time than logging conducted in selective locations over long rotations.

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GPO 846-242

Crouch, Glenn L. 1985. Effects of clearcutting a subalpine forest in central Colorado on wildlife habitat. USDA Forest Service Research Paper RM-258, 12 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Clearcutting 3-acre circular blocks on average and moist sites increased understory plant production and cover, but caused few changes in species composition. Plant moisture and crude protein content, and digestibility also increased after logging but, incidence of herbivore activity varied among species.

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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United States
Department of
Agriculture

Forest Service

**Rocky Mountain
Forest and Range
Experiment Station**

Fort Collins,
Colorado 80526

**Research Paper
RM-259**

An Evaluation of Herbage and Browse Production Estimators Used in the 1980 RPA Assessment

John E. Mitchell
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Acknowledgements

Sharon Woudenberg of the Intermountain Forest and Range Experiment Station provided numerous data extractions from the 1980 RPA Range/Multiple Resource Interactions data base. The critical review of Richard N. Ross (R–9) was instrumental in revising the final manuscript.

Acronyms

ID	–	Interdisciplinary
RPA	–	Forest and Rangeland Renewable Resources Planning Act
NFMA	–	National Forest Management Act
FRES	–	Forest-Range Environmental Study
MRI	–	Multiple Resource Interactions
PNC	–	Potential Natural Community (classification system)
PC	–	Productivity Class
CC	–	Condition Class
RU	–	Resource Unit
ML	–	Management Level
SCS	–	Soil Conservation Service
MLRA	–	Major Land Resource Area
IBP	–	International Biological Program

USDA Forest Service
Research Paper RM-259

March 1985

An Evaluation of Herbage and Browse Production Estimators Used in the 1980 RPA Assessment

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Abstract

Interdisciplinary team estimates of herbage/browse production used in the 1980 RPA Assessment were evaluated using three approaches. Estimates for nontimbered areas were mostly accurate; however, intrinsic relationships between forage production and productivity/condition classes were inconsistent. Production estimates for forested areas were more difficult to interpret, in part because of insufficient independent data. Intrinsic relationships also were inconsistent.

[1]*Headquarters is in Fort Collins, in cooperation with Colorado State University.*

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An Evaluation of Herbage and Browse Production Estimators Used in the 1980 RPA Assessment

John E. Mitchell and James B. Pickens

MANAGEMENT IMPLICATIONS

The multiresource data set developed by interdisciplinary (ID) teams for the Range and Multiple Resource Interaction parts of the 1980 RPA Assessment represented an immense task. It constitutes the only national-level multiresource data set available in the 1980s for assessments and appraisals. Moreover, there is little likelihood that this, or other intuitive data sets, will be soon replaced by more mechanistically quantitative models. If the Assessment data set is to maintain its usefulness, however, it should undergo updating and improvement. As expected, those ecosystems that are most commonly used for range livestock grazing are least needful of updating. Forested ecosystems comprise the majority of ecosystems whose forage production estimates fall outside of a proper conceptual framework.

Each of the three approaches taken in the present study has potential for amending different parts of the Assessment data set. The use of linear models to quantify the ID-team intuitive models in particular represents a consistent and documentable approach, especially for those ecosystems where independent data sources are lacking.

INTRODUCTION

During the past ten years, Congress has passed several laws that require federal agencies to make recurring assessments of present and projected resources coming from our Nation's forests and rangelands and future demands for these resources. The two laws assigning assessment responsibilities to the Forest Service are the Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 (P.L. 93–378) as amended by the National Forest Management Act (NFMA) of 1976 (P.L. 94–588). The RPA requires both supply-side and demand-side analyses; this paper deals with the supply side.

The first assessment of U.S. forests and rangelands was released shortly after the passage of RPA and NFMA (USDA Forest Service 1977a). To a great extent, the chapter on range from this assessment was taken from an earlier efficiency analysis of the U.S. forest and rangeland base emphasizing range management options and entitled the Forest-Range Environmental Study or FRES (Forest-Range Task Force 1972).

The second assessment was published in January 1980 (USDA Forest Service 1980). In this paper it is referred to as the Assessment. It was more comprehensive than the first, principally because more time was available to plan for the job and obtain required information.

In both FRES and the Assessment, an interdisciplinary (ID) team approach was used to estimate present resource outputs. The multiresource data set developed for the Assessment was used in two chapters: Range and Multiple Resource Interactions (MRI) (USDA Forest Service 1980).

ID-team estimates of output levels for multiple products used both in FRES and the Assessment were a function of a hierarchical partitioning of the forest and rangeland base of the United States according to ecosystem classification, ownership, site potential, condition, and intensity of natural resource management. Table 1 shows these categories as defined in FRES and the Assessment. If only on the basis of the number of combinations possible when linking the categories, the Assessment obviously involved a greatly expanded undertaking.

For the Assessment, the ecological classification was based wholly on Küchler's (1964) Potential Natural Vegetation system. An additional vegetation type, mountain meadow, was added because of its importance to range livestock production on western National Forest lands. The amended classification system was renamed Potential Natural Communities (PNC) to distinguish it from Küchler's system.

Within each PNC the land base was subdivided by ownership, productivity class (PC), and condition class (CC) categories. Each had four possible designations in the Assessment (table 1), providing 64 possible unique resource units (RU) for each PNC. The RU constituted the basic land management unit used by the Assessment ID teams in making multiresource production estimates.

Management options were defined in the Assessment as a combination of practices describing a specific management intensity or level (ML) for each of the three resource output groups; timber, range, and wildlife (table 1). Management practices were chosen to be consistent with existing technology. Timber had six possible MLs (1–6), range had six (A-E, X), and wildlife had three (1–3). In general, the MLs selected for each RU had the same options or a subset of the options chosen for that PNC. Approximately 10 management triplets were specified for most PNCs.

Once ML goals were designated, specific management practices were selected for each RU to attain the desired ML. These practices were classified into range, timber, and wildlife practices (table 2). It should be noted, however, that such designations are somewhat artificial because most management practices affect all resource outputs. This concept of joint resource production is especially important for timber management practices on forested communities (Hof et al. 1985).

Table 1.—Classification categories used in the FRES and 1980 Assessment.

OWNERSHIP

FRES	Assessment
1 Forest Service	1 Forest Service
2 Other federal	2 Bureau of Land Management
3 Nonfederal	3 Other federal
	4 Nonfederal

PRODUCTIVITY CLASSES (PCs)

Nontimbered *quartile*	Timbered *ft³/acre/yr*
1 High (1st)	120 +
2 Medium high (2nd)	85–119
3 Medium low (3rd)	50–84
4 Low (4th)	0–49

CONDITION CLASSES (CCs)

Nontimbered		Timbered[1]
FRES	Assessment	
1 Good	Good	Nonstocked
2 Fair	Fair	Seedlings and Saplings
3 Poor	Poor	Poles
4	Very Poor	Sawtimber

MANAGEMENT LEVELS (MLS)

FRES (Range practices only)

1. Environmental management without livestock
2. Environmental management with livestock
3. Extensive management of environment and livestock
4. Intensive management of environment and livestock
5. Environmental management with livestock production maximized
6. Exploitive management

1980 ASSESSMENT

Range

A.
B.
C.
D.
E.
X.

Same as for FRES; levels E and X were not considered in combination with any timber or wildlife management practices.

Timber

1. No commercial use
2. Minimal management without assured regeneration
3. Minimal management with assured regeneration
4. Level 3 with commercial thinning
5. Level 4 with precommercial thinning
6. Level 5 plus intensive silviculture such as fertilization

Wildlife

1. No management
2. Manipulation of vegetation
3. Level 2 with physical structure development

[1] *For technical description of these classes, see FSH 4809.11, Forest Survey Handbook.*

Thirteen resource outputs were estimated for the Assessment, nine less than under FRES. Of these, only nine categories were production levels. The others were in the form of indices or abstract percentages of land area. Those resource outputs defined quantitatively under FRES and the Assessment are listed in table 3.

In summary, the Assessment Range and MRI analyses were based on an intuitive (ID-team) approach, patterned after the earlier FRES. Inituitive models are not based on mechanistic mathematical descriptors or the statistical analysis of field data, but rely on experts to make estimates based on their training and experience (Joyce et al. 1983). Intuitive approaches are being increasingly used where environmental variables are difficult to quantify (Cooper and Zedler 1980). The next assessment, due by the end of 1989, will likely be conducted under a similar format, given the time constraint and lack of other national multiresource data sets. An important question to be asked by those responsible for the next assessment is whether the multiresource data set used in the 1980 Assessment is sufficiently accurate to be used again without modification, or whether

Table 2.—Management practices used in the 1980 assessment, by resource output group.

Management practice	Units/100 M acres
Range	
Fertilization	M acres
Irrigation	M acres
Water control	M acres
Mechanical vegetation control	
Low Cost	M acres
High cost	M acres
Vegetation manipulation	
Chemical	M acres
Biological	M acres
Fire	M acres
Debris disposal	M acres
Mechanical soil treatment	M acres
Seeding	M acres
Rodent control	M acres
Insect and disease control	M acres
Small water development	Sites
Large water development	Sites
Fence	Miles
Timber thinning	M acres
Timber	
Planting	M acres
Direct seeding	M acres
Site preparation for—	
Natural regeneration	M acres
Planting and seeding	M acres
Animal control for—	
Reforestation	M acres
Timber stand improvement	M acres
Precommercial thinning	M acres
Release and weeding	M acres
Fertilization of established stands	M acres
Seed production areas	M acres
Selection and care of superior trees	M acres
Prescribed burning to control understory	M acres
Access roads for timber production	Miles
Cutting method	
Shelterwood and seed tree	M acres
Clearcutting	M acres
Salvage	M acres
Commercial thinning	M acres
Selection (high-grading)	M acres
Selective	M acres
Wildlife	
Water developments—upland	Sites
Seeding and planting	M acres
Liming and fertilizing	M acres
Fencing	Miles
Prescribed burning—uplands	M acres
Clearing	M acres
Brush and shrub management	
Mechanical	M acres
Chemical	M acres
Biological	M acres
Pruning	M acres
Thinning—release	M acres
Mechanical soil treatment	M acres
Dens and nest structures	Structures
Perch and nest structures	Structures
Brushpiles and covers	Brushpiles
Streambank stabilizers	Sites

changes/updating will be required. A third alternative, building a completely new data set, may be infeasible under existing financial and time limitations.

The purpose of this study was to evaluate the herbage/browse production estimates used in the 1980 Assessment. Specifically, the objective was to ascertain whether these estimates were accurate, based on median values for each PNC in relation to other sources of information, and followed reasonable patterns within the PNCs in relation to changing PC and CC. In the book of procedures used by the ID teams (USDA Forest Service 1977b), herbage and browse production was defined as:

> Total air-dry weight of the current year's growth of leaves and twigs of shrubs, woody vines, and trees available for animal consumption, measured in pounds per acre to the nearest 100 pounds. For purposes of this exercise, herbage will also include growth of non-flowering, non-woody plants, such as ferns, mosses, lichens, and fungi.

This definition encompassed all plants, including members of thallophyte divisions and higher plants normally not considered as sources of forage. The only criterion for inclusion was availability. Such a definition is more inclusive than that commonly accepted in range management, which generally restricts the term "forage" to include only those plants having some food value to grazing or browsing animals (Sampson 1952). Consequently, the Assessment estimates would be expected to have larger values than anticipated for some PNCs, especially those with woody understories. In this paper, however, the term forage will be used synonymously with the Assessment definition of herbage and browse.

METHODS

By their nature, ID-team estimates present unique problems in data validation. First, assumptions built into the Assessment data, such as those to ameliorate effects of inclusions of unproductive areas within a PNC, make direct comparisons with field data difficult. The definition of herbage/browse used in the Assessment also constituted an assumption. Second, much published information comes from research studies, and as Bruce (1977) suggests, resource production data based on research plots are commonly different than actual production associated with the larger ecosystems such plots were designed to represent.

Perhaps the major impediment to validating the production estimates used in the 1980 Assessment resulted from the complex system of variables that the ID-teams had to consider, especially in terms of management practices. No independent data sets exist that depict the effects of site, successional status, and management on resource production. If the Assessment data for a given resource output are represented in an *n*-dimensional array, then the problem of comparing actual data with it becomes one of fitting these data into the array on the

Table 3. Resource categories estimated quantitatively in the FRES and 1980 Assessment.[1] (Units are on an acre^{-1} year $^{-1}$ basis, except for storm runoff.)

Resource category	FRES	Assessment
Livestock stocking rate	AUM	AUM
Herbage and browse production	Ton	Pound
Livestock output value	Dollar	--
Wild ruminant grazing	--	AUM
Wood growth	Cubic feet	Cubic feet
Wood harvest	--	Cubic feet
Water yield	Acre-foot	Inches
Quality water yield	Acre-foot	--
Storm runoff	Inches/storm^{-1}	Inches/storm^{-1}
Sediment	Ton	Ton
Dispersed recreation	Visitor-day	Visitor-day
Employment	Man-hour	--

[1]*Dash indicates no estimate made.*

basis of assumptions that are often tenuous. Given the constraints imposed by the problems outlined above, the following three procedures were employed here to evaluate the range data base: (1) intrinsic verification, (2) comparison with field research, and (3) comparison with Soil Conservation Service range site information.

First, the Assessment data were examined intrinsically for relationships between herbage and browse production and the various site and management descriptors, especially productivity and condition classes. Such relationships portray the formal expression of the ID teams' perceptions of production relationships of actual ecosystems. Consequently, the examination served as a verification of the theoretical "model" embodied in these perceptions (Nolan 1972). The next logical step, that of model validation, could not be undertaken because of the lack of real-systems data. Model validation tests a theoretical model's representation of a real system—which in this case constituted forage responses to different RUs and management.

With rare exceptions, as nonforested ecosystems retrogress from good/excellent to poor condition, actual forage production decreases even when palatability is not considered, because of immoderated environmental factors affecting plant growth (Mitchell 1983a). This qualitative relationship between range condition and primary production has been documented (Weaver and Albertson 1940, Strickler and Hall 1980). The few quantitative studies (Geobel and Cook 1960, Klipple and Costello 1960, Launchbaugh 1969) suggest the magnitude of reduction in productivity to be in the order of 15% to 50%, depending on PNC and the severity of depletion defining poor condition range. Reductions beyond 50% are always feasible because, by definition, the end point of retrogression is bare ground.

Information relating forage production to PC is, like that dealing with CC, inadequate for the purpose of making specific predictions. In what is perhaps the only paper dealing with this subject, Mueggler and Stewart (1981) examined 13 rangeland habitat types in Montana and found average production on poor sites to deviate around two-thirds of the average production on good sites for the same habitat type.

To summarize, from field research one can conclude that models of forage production on nonforested range should provide for decreases due to both range condition and site potential. Levels of reduction are uncertain, especially under the definition of herbage and browse provided in the 1980 Assessment; however, it appears that, when specific information is unavailable, production should be reduced on the order of one-fourth to one-half for both low site potential and poor range condition.

The relationship between forage production and CC on forest land has been well studied, especially in forest and woodland zones where grazing has been of historical importance (Ffolliott and Clary 1982). Basically, production decreases in response to overstory development in the tree canopy. Unfortunately, little is known concerning trade-offs between forage production and site index (i.e., PC) on timbered range (Clary et al. 1966), and what has been published provides ambivalent conclusions (Basile 1971).

A linear model was used to describe numerically the association between PC and CC as they affected forage production estimates in the Assessment.

$$Y_{ij} = \alpha + \beta_i(\mathrm{PC})_i + \gamma_j(\mathrm{CC})_j + \delta_{ij}(\mathrm{PC})_i(\mathrm{CC})_j \qquad (1)$$

Y_{ij} was forage production for the i^{th} PC and j^{th} CC. The four parameter sets, α, β, γ, δ, represented the intercept, main effect of PC, main effect of CC, and the PC-CC interaction. In the model, PC and CC were dummy variables. Since only one observation, the ID-team estimate, existed per cell, the model provided a perfect fit of the data set, and the error sum of squares was zero.

Using a model to portray forage production in relation to PC and CC served three useful purposes. First, it quantified the influence that PC had in relation to CC. Second, it showed whether a synergistic effect existed between PC and CC to increase (or decrease) forage production on higher class sites in good condition. Third,

the model made missing data and apparent data entry errors (either in the Assessment data base or this study) easy to discern, primarily because they created outliers among the interaction coefficients, δ_{ij}.

The ID teams taking part in the 1980 Range and Multiple Resource Interaction Assessments were trained and completed their work in one of two sequential workshops, held both at Fort Collins, Colo., and Athens, Ga. The two Fort Collins workshops were responsible for the western PNCs, while the Athens workshops handled the eastern PNCs. There were six team leaders in Fort Collins and four in Athens. Each leader was responsible for two ID teams which met in successive 2-week periods. Individual team members were assigned PNCs, and asked to bring data and other background information to their workshop.

As part of the process for intrinsically evaluating the data set, the PNC linear model coefficients were subjectively compared on the basis of (1) where the ID teams assembled, (2) between ID teams within the two workshop locations, and (3) between 2-week periods for the Fort Collins workshops only. Specifically, the comparison was made to see whether visible differences existed depending on (1) where the ID teams received training, (2) who the ID-team leaders were, or (3) the experience each ID-team leader obtained after going through one 2-week period. To do this, the linear model coefficients were examined for main (PC versus CC) effect and level of interaction. The model coefficients for each PNC were classified into one of five main-effect categories and three interaction categories.

Main-effect categories:

P+	PC dominates, CC has no effect
P	PC effect exceeds CC effect
=	PC and CC effects are approximately equal
C	CC effect exceeds PC effect
C+	CC dominates, PC has no effect.

Interaction categories:

0	No interaction effect (9 cells blank)
+	Weak interaction effect (3–8 cells blank)
++	Strong interaction effect (< 3 cells blank)

The resulting tabular information was then scrutinized for explicit patterns and relationships that would portray the confounding effects being sought.

A second evaluation procedure consisted of comparing actual field data, obtained primarily from research reports, with Assessment estimates wherever commensurable data became available. In all instances, published field data were insufficient to adequately describe the forage production response surfaces represented in the Assessment by the various site/management descriptors. Therefore, comparisons, themselves, became intuitive in nature.

Finally, Assessment data were compared with herbage production estimates contained in range site descriptions developed by the Soil Conservation Service (SCS) of USDA. Under the range site concept, rangeland is classified according to its potential plant community composition and productivity (Shiflet 1973). The classification scheme resembles that of the habitat type used in classifying forests (Daubenmire 1952), except that productivity is not a factor in defining habitat types.

Descriptions have been written for hundreds of range sites, mostly located within the 17 western range states. They include estimates of average forage production, during both favorable and unfavorable years, by range condition. Although the forage production estimates are based on actual field data, they are intuitive to the extent that each represents a judgment by a locally experienced range conservationist who must synthesize these information sources into two single values.

Range site descriptions are developed within individual states under the auspices of each SCS state office. However, they are categorized under a hierarchical classification according to land resource regions and major land resource areas (MLRA) (USDA SCS 1981). MLRAs are differentiated on the basis of soils, climate, water resources, and land uses, and are not affected by political boundaries. Similar range sites can occur, therefore, in different states within the same MLRA. Sometimes they also are found in different MLRAs.

Range site descriptions are more detailed than PNCs, even when the latter are stratified by PC. Because of this disparity, an algorithm was required to match Assessment data with their respective range site estimates. The procedure consisted of matching PNCs and MLRAs on their respective maps, and choosing target MLRAs for more detailed analysis. Then, within an MLRA, range sites were selected to represent the entire span of forage on understory production within that MLRA.

Selection of range sites was based principally on species composition at climax (i.e., CC1), as identified in each range site description. (For a discussion of the concepts of succession and climax, see Daubenmire 1968.) When only a few pertinent range sites were available, all were listed for comparison purposes. Alternatively, when many range sites comprised an MLRA, a sample was selected for comparison using the following guidelines:

1. The sample represented the range of production.
2. The sample depicted the sites most representative of the MLRA, especially where production was not evenly or normally distributed across range sites.
3. Sites selected for exclusion tended to be of minor importance in terms of land area.

Of the 107 PNCs contained in the Assessment data set, herbage and browse production estimates are contained in all but two, desert and mangrove. For purposes of this study, however, only major forage-producing PNCs were evaluated, i.e., those that are important as rangeland (Stoddart et al. 1975) because of their species composition or size. Table 4 lists the 32 PNCs examined. They account for more than two-thirds of the land area and three-fourths of the total mass of forage produced, according to the Assessment data set. Of these 32, only 24 could be compared to SCS range site descriptions because of the lack of range site descriptions for forested communities, especially in the eastern United

Table 4.—List of PNCs for which herbage/browse production estimates used in the Assessment were examined.

PNC	Shrub and grassland	PNC	Forest and woodland
32	Great Basin Sagebrush	2	Cedar-Hemlock-Douglas-fir[1]
34	Saltbush-Greasewood	5	Mixed Conifer[1]
41	California Steppe	10	Western Ponderosa
47	Grama-Galleta Steppe	11	Douglas-fir
49	Sagebrush Steppe	14	Western Spruce-Fir[1]
52	Grama-Tabosa Shrubsteppe	21	Pinyon-Juniper Woodland
53	Trans-Pecos Shrub Savanna	26	California Oakwood
54	Mesquite-Acacia Savanna	91	Oak-Hickory[1]
56	Foothills Prairie	95	Appalachian Oak[1]
57	Grama-Needlegrass-Wheatgrass	101	Oak-Hickory-Pine[1]
58	Grama-Buffalo Grass	102	Southern Mixed Forest[1]
59	Wheatgrass-Needlegrass	103	Southern Floodplain Forest[1]
60	Wheatgrass-Bluestem-Needlegrass		
62	Bluestem-Grama Prairie		
66	Bluestem Prairie		
67	Nebraska Sandhills Prairie		
75	Cross Timbers		
76	Mesquite-Buffalo Grass		
77	Juniper-Oak Savanna		
107	Mountain Meadow		

[1] *No comparable SCS site descriptions available.*

States. In addition to those listed in table 4, several other PNCs were included in the comparison with research data, but only to further understanding of the results.

RESULTS

Intrinsic Relationships

An examination of the way in which herbage and browse production estimates were effected by PC and CC provided an interesting perspective on the nature of the Assessment data set. In general terms, production on grassland-shrubland PNCs varied more widely in response to PC than it did with changing CC. Alternatively, on forested and woodland PNCs, the opposite occurred. Herbage and browse production for selected MLs for the PNCs evaluated are presented in appendix 1 by PC and CC.

Nonforested PNCs

Twenty nonforested PNCs were examined (table 4). Sixteen of these were dominated by graminoids, either as grasslands or under mostly open shrub or tree synusiae. As climax communities, about one-half were represented by warm-season, sod-forming grasses, and the other half by cool-season bunchgrasses. Together, they encompassed a wide variety of ecosystems, not only in their structure but in their successional dynamics.

Five of the non-forested PNCs (32, 41, 47, 49, 52) showed no decline in productivity across CC (table 5). Although they are grouped together in terms of PNC identification number, they possessed no common characteristics that allowed them to be clustered ecologically. The proportional relationship of forage production to PC was similar for each of these five PNCs; i.e., production for PC1 tended to be three to five times higher than for PC4. Consequently, the conceptual forage production model for these five PNCs embodied in the ID-team estimates states that production is not affected by range condition; however, site potential can have a great influence.

Four PNCs (56–59) had identical main-effect coefficients for both PC and CC (table 5); i.e., forage production responded equally to changing PC and CC. Each of the four PNCs had similar interaction coefficients, suggesting a positive synergistic effect between PC and CC possessing the same symmetry as the main effects. Although the PNCs, numbered sequentially, were contiguous to one another in the northern and central Great Plains, they fall into two groups ecologically and suggest an ID-team effect. PNCs 56, 57, and 59 were dominated by cool-season wheatgrasses and needlegrasses at climax, while PNC 58 was represented by blue grama and buffalograss, warm-season sod grasses of the high plains (Küchler 1964). In fact, the species composition of PNC 56 resembles that of PNC 49 much more closely than it does PNC 58.

Only one PNC, 54, showed a greater main effect for CC than for PC (table 5). In addition, a strong positive interaction effect between PC and CC was depicted in the model for PNC 54. The ID team had apparently considered the influence of increasing woody growth during retrogression (i.e., decreasing CC) to a greater extent than the ID teams evaluating other PNCs with a brush or savanna overstory, such as PNC 32, 49, 76, and 77.

The remaining ten nonforested PNCs all could be characterized by greater main effects for PC than for CC (table 5). In ranking these PNCs by the ratios of model

Table 5.—Coefficients of linear model of forage production estimates for selected PNCs, as based on ID-team estimates, contained in the 1980 RPA data base.

PNC-ML	α_0	β_1	β_2	β_3	γ_1	γ_2	γ_3	δ_{11}	δ_{12}	δ_{13}	δ_{21}	δ_{22}	δ_{23}	δ_{31}	δ_{32}	δ_{33}
Grassland-Shrubland PNCs																
32C	400	1100	800	400												
34C	0	750	500	250	250	150	50									
41C	800	2400	2000	800												
41D	900	3600	2800	900												
47B	200	300	200	100												
47D	200	300	300	100				100	100	100						
49C	500	1500	1000	500												
49D	0	2200	1600	1100	0	0	0	300	300	0	200	200	0	100	100	100
52B	100	400	200	100												
53C	200	1000	0[1]	400	300	200	100	200	200	100						
53D	200	1800	0[1]	1000	300	200	100	−200	−200	−100				−300	−200	−100
54B	200	300	200	100	800	500	300	1200	900	400	800	600	200	400	300	100
54E	300	400	300	100	900	600	400	900	1100	500	900	700	200	500	400	200
56C	200	300	200	100	300	200	100	1200	800	400	700	500	300	400	300	100
57C	100	300	200	100	300	200	100	900	600	300	600	400	200	300	200	100
58C	100	300	200	100	300	200	100	300	200	100	200	100	100	100	100	
59C	100	500	300	100	500	300	100	1400	800	300	800	600	300	300	300	200
59D	100	800	400	200	800	500	200	2000	1100	400	1200	900	500	400	400	200
60C	600	900	600	300	600	400	200	900	600	300	600	400	200	300	200	100
60D	700	1000	600	300	500	300	200	900	600	300	700	500	300	300	200	100
62C	800	1200	800	400	400	300	100	600	400	200	400	300	200	200	100	100
62D	1000	1400	900	400	200	100	100	400	200	300	300	200	300	200	100	200
66C	1000	4000	2500	1200	700	600	400	1100	1100	100	200	200	−100	100	0	0
66D	1900	4900	2500	1200	400	200	0	200	200	0	200	200	0	0	0	0
67C	600	3300	2200	1100	400	200	0	0	−100	0	0	100	0	0	100	0
75C	900	1500	900	600	1200	800	400	1200	800	400	900	600	300	300	200	100
76B	800	2200	1500	700	400	300	200	100	100	0	0	0	0	100	100	0
76D	800	2800	2000	700	400	300	200	200	200	0	0	−500	0	100	100	0
77D	1200	3600	1200	600	1200	600	0	0	−600	−1200	1200	600	0	600	0	0
107C	200	2800	2000	800	800	400	200	200	200	0	0	0	−200	200	200	0
107D	400	3100	2000	800	700	400	200	300	100	100	300	200	0	300	200	0
Forested PNCs																
2A2	100				1400	300	−50	1500	100		1000	100		500	100	
2A5	100				1400	300	−50	500	100	50	200	100	50		100	50
5B	1000	−500	−500	−400	2000	1500	300	3500	3000	200	2000	1800	100	−600	−400	−200
10B	400				400	−300	−200									
10D	600				300	−500	−100									
11B	100	600	600	400	400	200	100	2900	1100	200	2900	1100	200	800	200	−100
14B3	0				1200	500	100	3000	2500	900	1800	1000	300	1000	500	200
14C5	100	400			1100	900	200	2400	1600	900	2000	1000	700	1000	600	500
21B	100	500	300	100	100	100		200	100	100	200	100	100	200	100	100
21D	100	700	600	300	200	100	100	200	200	100	100	100		100	100	
26B	2900					300	100									
26D	3500				700	1000	100									
91A	300				900	300	400	−400	−300	−500	−400	−300	−500	−200	−200	−200
91D	1500	2500	2500	500										−500		
95C	600	−100	−100	−100		−100	−100	300	200	100	300	200	100	200	200	100
101B	600	−100	−200	−100	400	−400		300	900	100	400	1000	300	300	300	
102A3	400	800	400	400	600	400		1200	600		600	300		600	300	
102B4	1000	500				500	−200		200	−100						
102A6	1000	500			−500	500	−200	−250	200	−100						
103A2	100	200	200	100	200	500		500	100	−100	500	100	−100	400		
103E	12000															

[1]*Zero value in main effect due to missing data.*

coefficients for PC1:CC1, the median value obtained was approximately 4.25:1. Two PNCs, 60 and 75, approached the symmetry between PC and CC found in the four previously discussed. At the other extreme, PNC 66, under intensive range management, depicted a relationship wherein PC affected forage production over CC by more than an order of magnitude.

Except for situations where data were missing or apparent data entry errors had occurred, all interaction coefficients were positive and reasonably consistent, indicating a positive synergistic effect between increasing PC and CC. Missing data for PC2 were found in PNC 53. This exclusion can be explained by the absence of PC2 from the land base of PNC 53. In the automated editing

process, all production estimates were dropped from the data base if the RU did not exist in the land base. Apparent data outliers, i.e., those disrupting the smooth response surface of production in relation to PC versus CC, were found in seven of the selected nonforested PNCs (table 6).

Table 6.—List of PNCs used in the 1980 Assessment having forage production estimates that are questionable, based on internal inconsistencies.

PNC	Range-Forest ML	Location of outlier PC	Location of outlier CC
Nonforested PNCs			
54	E	1	2
62	D	1, 2, 3	2 versus 3
66	C	1	Magnitude of drop from CC2 to CC3
67	C	1	2
76	D	2	2
77	D	1	4
107	A	2	4
Forested PNCs			
91	D	3	1
101	B	4	2

Forested PNCs

Unlike the situation for nonforested PNCs, model coefficients describing forage production in relation to PC and CC on forested PNCs were irregular and more difficult to interpret. For example, main-effect coefficients on half of the 12 PNCs examined contained negative values, which meant that forage production actually decreased at some point with increasing PC or CC (table 5). Such an inverse association between forage productivity and PC may be seen in PNC 5, while PNC 10 portrays the same situation in relation to CC.

A possible explanation exists for forage production increasing across decreasing PC; i.e., a low-site stand might tend to be more open because of limiting ecological factors, such as thin soil, resulting in less light attenuation by the forest canopy and increased understory growth (Ffolliot and Clary 1982). No comparable explanation is evident for an inverse relationship between productivity and CC, however.

In general, CC had a greater main-effect influence on production than did PC (table 5). This intuitive model provided a logical description of what actually occurs in forested ecosystems where the controlling factor is often the overstory canopy (Ffolliott and Clary 1982). Exceptions were confined for the most part to management triplets containing intensive range management levels (i.e., D), which ostensibly included timber thinning and chemical vegetation manipulation practices.

PNCs 11, 21, and 102 showed tendencies for a larger main effect due to PC at less than intensive levels of range management. Of these, PNC 21 may most reasonably be expected to respond to PC as depicted because of the wide diversity of sites occupied by pinyon-juniper associations. Jameson and Dodd (1969), for instance, showed that production of herbaceous vegetation varies widely in Arizona pinyon-juniper communities, depending on soil type (i.e., PC).

Identifying apparent data entry errors or other outliers proved to be somewhat more difficult for the forested PNCs because the interaction coefficients varied widely in reaction to the inverse relationships between forage production and PC/CC, as discussed above. The two forested PNCs having identifiable outliers are shown in table 6.

The inspection of linear model coefficients to compare ID-team characteristics (locations of training, ID-team leader, and experience effect resulting from successive workshops) provided interesting results. For nonforested ecosystems there was a tendency to confound the team leader and experience effects due to allocation of PNCs to groups for those PNCs which we evaluated (table 7). That is, five of the seven PNCs covered in the first session were handled by ID teams 2 and 5. During

Table 7.—Relationships between linear model coefficients, as expressed by main-effect emphasis and degree of interaction, and ID-team characteristics as identified in the 1980 RPA Assessment

ID-team location	Workshop session	ID-team number	PNC	Main effect[1]	Degree of interaction[1]
		Nonforested PNCs[2]			
Fort Collins	1	1	47	P+	0
		2	56	P-C	+ +
		2	57	P-C	+ +
		4	41	P+	0
		5	32	P+	0
		5	34	P	0
		5	49	P+	0
	2	1	52	P+	0
		1	53	P	+
		2	59	P-C	+ +
		4	107	P	+
		5	67	P	+
		6	58	P-C	+ +
		6	60	P	+
		6	62	P	+ +
		6	76	P	+
		Forested PNCs			
Fort Collins	1	2	11	P	+ +
	2	2	14	C+	+ +
	1	3	2	C+	+
	1	3	10	C+	0
	1	4	26	C+	0
	1	5	21	P	+ +
	1	6	5	C+	+ +
Athens	1	1	102	P-C	+
	2	1	95	P-C	+ +
	1	3	91	C+	+ +
	1	3	101	P-C	+ +
	2	3	103	P-C	+

[1] *Categories have been defined in the Methods Section.*

[2] *Nonforested PNCs examined at Athens included 54, 66, 75, and 77.*

[3] *Fort Collins Workshop 1, March 21 to April 8, 1977*
Workshop 2, April 11, to April 22, 1977
Athens Workshop 1, March 29 to April 15, 1977
Workshop 2, April 12 to April 29, 1977.

the second session, however, most of the PNCs (six of nine) were handled by two different ID teams (numbers 1 and 6). Therefore, there was little opportunity to examine the ID team-session interaction.

Results of the comparison of linear model coefficients with ID-team training/work site, ID-team (leader) identification, and ID-team leader experience level (period 1 versus period 2) are presented in Table 7. Looking first at nonforested PNCs addressed in Fort Collins, it is obvious that, except for the estimates provided by team 2 and one other PNC (34), all of the linear models developed during the first session contained main-effect responses to PC only and had no interaction effects. On the other hand, models developed during the second session contained, with one exception (PNC 52), main-effect responses to both PC and CC and had interaction effects. There were insufficient nonforested PNCs from the Athens site to warrant examination.

While the nonforested situation was related to workshop session number (confounded with ID-team effect), model coefficients emanating from ID-team estimates of forested PNCs did not (table 7). Here, the major division appeared to result from location. The ID-team meeting at Fort Collins, with two exceptions (PNCs 11 and 21), found CC to provide the only nonnegative main effects, while the Athens-based ID teams tended to provide main-effect responses to both PC and CC. Several of the main-effect coefficients were negative, however, making comparative interpretations more difficult. Interaction effects were present for nearly every forested PNC.

Comparison with Field Data

Sagebrush-Grass Ecosystems (PNCs 32 and 49).—Küchler differentiated between PNCs 32 and 49 by stating that the former was a shrub community and the latter was a grassland topped by a shrub synusia; i.e., the differentiation was on the basis of grass abundance. Other authors, however, have made no attempt to divide the sagebrush-grass region into major subtypes (Tisdale and Hironaka 1981).

Although the sagebrush-grass region has received extensive research, little has been published on total production of native vegetation. For example, Robertson (1971) compared production of grass species on a native sagebrush site in northern Nevada to one reseeded with crested wheatgrass. His reported values of 200 and 925 lb/acre, respectively, unfortunately do not include forb and shrub production. Robertson's site had been ungrazed for 30 years, but had been eroded during earlier times; therefore, it logically would have fit the PC-CC-ML code of 3–1–A or 4–1–A. These values were 800 and 400 lb/acre, respectively, for PNC 32 and 1,000 and 500 lb/acre for PNC 49. (Note: Recall from previous section that CC had no effect on forage production in the Assessment data base for the two sagebrush PNCs.)

In an earlier study Passey and Hugie (1963) followed total herbage and shrub biomass for 4 years on a protected, ungrazed site in southern Idaho. They recorded values of approximately 600–1,000 lb/acre, with an average of 800 lb/acre. Based on the study area description, one would classify their site as PNC 49 with a PC-CC-ML of 1–1–A or 2–1–A for comparison purposes; the Assessment estimates were 2,000 and 1,500 lb/acre.

Blaisdell (1958) reported on 20 years of vegetation composition and yield data collected from large enclosures at the U.S. Sheep Station in eastern Idaho. His estimate of average total grass, forb, and shrub peak biomass was 820 lb/acre, which closely approaches the estimate provided by Passey and Hugie (1963) and tends to corroborate the conclusion that Assessment estimates for productive sites (PC = 1,2) in the sagebrush-grass region appear too high.

Mixed-Grass Plains (PNCs 59 and 57).—During the early 1970s, two comprehensive study sites were maintained on the mixed-grass Great Plains under the auspices of the International Biological Program (IBP). In western North Dakota, Lauenroth and Whitman (1977) estimated total above-ground production to range from 2,150 to 2,700 lb/acre on an ungrazed site equivalent to PNC 59 in good condition (PC-CC-ML = 2–1–A). The Assessment estimate for this site was 1,700 lb/acre.

The Cottonwood Range Field Station, located in western South Dakota (PNC 59), has maintained experimental pastures that have been subjected, nearly continuously, to light, moderate, and heavy grazing since 1942. By the mid–1950s, these pastures were in low excellent, good, and fair conditions, respectively (Lewis et al. 1956). At that time, Lewis et al. (1956) measured forage production in the draws (PC1), on north slopes (PC2), south slopes (PC3), and ridges (PC4). Table 8 compares their sample means with comparable Assessment estimates. Subjectively, it appears that the Assessment figures are reasonable for the combinations of PC1 and 2, and CC1 and 2; however, they are increasingly underestimated at the lower combinations of PC and CC.

Reed and Peterson (1961) summarized a grazing study lasting from 1932 to 1946 on mixed-grass prairie near Miles City, Mont. (PNC 57). They reported production estimates of bench sites (PC3) and bottomland (PC1) under both light (CC1) and heavy (CC3) grazing (table 9). Their values are reasonably close to the ID-team

Table 8.—Average (1952–1955) forage production (lb/acre) on experimental pastures at the Cottonwood Range Field Station (South Dakota) in comparison to assessment estimates (ML = C).

	PC			
CC	Draws 1	N-Slopes 2	S-Slopes 3	Ridges 4
Field data (Lewis et al. 1956)				
1	2885	1389	1289	1059
2	2231	1343	1300	1009
3	2509	1188	1098	1069
Assessment estimates (PNC 59: Wheatgrass-Needlegrass)				
1	2500	1700	1000	600
2	1700	1300	800	400
3	1000	800	500	200

Table 9.—Forage production (lb/acre) after fifteen years of grazing research on Mixed-Grass Prairie near Miles City, Mont., in comparison to assessment estimates (ML = C).

	PC	
	Bottomland	Benches
CC	1	3
Field data (Reed and Peterson 1961)		
1	1139	517
3	770	395
Assessment estimates (PNC 57: Grama-Needlegrass-Wheatgrass)		
1	1900	800
3	800	400

estimates in the Assessment, and would have probably been closer if 1945, the year in which their forage biomass estimates were taken, had not been a dry year.

Short-grass Plains (PNC 58).—The cornerstone of range research on the shortgrass plains has been conducted at the Central Plains Experimental Range near Nunn, Colo. Klipple and Costello (1960) summarized a decade of herbage production during the 1940s on pastures grazed at light, moderate, and heavy intensities. They found total production of all vegetation to remain the same for lightly and moderately grazed pastures (i.e., about 600–650 lb/acre), but to decrease by one-third under heavy grazing (420 lb/acre). These values fall into the mid-range of ID-team estimates for PNC 58; however, the proportional drop from CC1 to CC4 within a given PC somewhat exceeds the 33% cited by Klipple and Costello (1960), depending on whether the heavily grazed pastures fell in CC3 or CC4. No pastures approached the 800–1,000 lb/acre contained in the Assessment under high combinations of PC and CC for PNC 58.

Sandhills Prairie (PNCs 67 and 63).—At the Eastern Colorado Range Station near Akron, total herbage yield on lightly (CC1), moderately (CC2), and heavily (CC3) grazed pastures were monitored between 1964 and 1968. The investigators (Sims et al. 1976) reported averages of 1,430, 1,210, and 930 lb/acre for the three respective pastures. However, production had evidently not stabilized on the heavily grazed pasture by the study's end, and the actual disparity between CC1 and CC3 may be somewhat greater. According to L. Rittenhouse of Colorado State University (personal communication), the averages provided by Sims et al. (1976) are reasonable for the western (drier) end of the sandhill prairie region.

Assessment estimates for PNC 63 (sandsage-bluestem prairie; not discussed elsewhere in this report) closely track the Akron research results. Taking an "average" PC of 2.5, production estimates for CC1, CC2, and CC3 were 1,400, 1,350, and 1,150 lb/acre, respectively. Those for the true Nebraska sandhills prairie (PNC 67), however, are approximately double those for PNC 63, except for PC4, where they are comparable.

Tallgrass or True Prairie (PNC 66).—Although it originally constituted a vast area from the Canadian border to Texas and eastward (wedgelike) as far as Indiana (Küchler 1964), the tallgrass prairie has been reduced to small, scattered remnants over much of its range. The Flint Hills of Kansas and Osage Hills of Oklahoma constitute the only appreciable tracts of native prairie left, primarily because they are underlain by soils too rocky to plow. Of the original 250 million acres, less than 20 million acres remain in native vegetation (USDA Forest Service 1936). Much of the true prairie has subsisted in good condition, however, because of its recovery from drought and grazing pressure during earlier years (Weaver and Hansen 1941).

In northwestern Minnesota, Smeins and Olsen (1970) measured peak standing crop of an upland, moist tallgrass prairie site in pristine condition at 3,980 lb/acre. In central Missouri, Kucera et al. (1967) found production to vary according to fire, especially in the eastern parts of the prairie region. Peak standing crop on unburned sites was approximately 4,500 lb/acre, while it increased by 15% to 100% on burned sites.

Old (1969) corroborated Kucera et al.'s work in eastern Illinois, where she reported herbage biomass levels of 4,750 lb/acre on recently burned prairie and 2,400–3,000 lb/acre on burns 3 to 4 years old. In Iowa, Ehrenreich and Aikman (1963) reported that burning did not greatly increase production of native prairie, i.e., 3,300 lb/acre on unburned plots versus 3,600–4,250 lb/acre on burned plots.

The importance of what is meant by production (Mitchell 1983a) is nowhere greater than when considering the true prairie. Here, the difference between production rates and peak community biomass for prairie ecosystems can be substantial. Parton and Risser (1980), for example, predicted net aboveground primary production on an Oklahoma tallgrass prairie to be 4,830 lb/acre/yr under no grazing, while peak standing crop was only 2,460 lb/acre. Under moderate grazing, production and peak standing crop were estimated at 4,980 lb/acre/yr and 2,290 lb/acre, respectively. The production estimates presented in this report were apparently, for the most part, measures of peak standing crop or end of growing season biomass.

The literature, as shown above, reports a broad range of herbage production across the true prairie, depending on a number of interacting factors like site factors and fire history. The ID-team estimates for PNC 66 nicely bracket these production figures. For example, given PC2 and range ML = C, herbage production estimates decline from 4,400 lb/acre under CC1 to 3,500 lb/acre under CC4. As with some other PNCs evaluated, the highest (PC1, CC1; PC1, CC2) and lowest (PC4) production estimates appear somewhat extreme; however, literature values are not available to either support or refute them.

Cedar-Hemlock Zone (PNCs 2 and 12).—In the Pacific Northwest, cedar-hemlock sites (PNC 2) are often dominated by Douglas-fir, except on old-growth stands (Franklin and Dyrness 1973). Understory abundance is primarily a function of overstory canopy closure in these dense forests; an abundance of forage exists in the open-

ings, while closed stands are considered unsuitable for grazing (Mitchell 1983b).

Long and Turner (1975) described a decreasing exponential relationship between overstory canopy and understory shrub abundance in young, productive Douglas-fir stands in western Washington (PC1). At a stand age of 20 years (CC2), understory biomass, including woody material, was estimated at 6,000 lb/acre. Two older stands (CC3) had understory biomass levels of 2,450 and 3,780 lb/acre, still a substantial amount.

In a similar study, Webber (1977) found understory biomass, approximately 350 lb/acre, to be much less than that reported by Long and Turner. However, Webber's stand, estimated to be 15–20 years old, was overstocked with trees and located on an area of low site potential (PC4). Natural regeneration occurred on the sites of both studies (forest ML = 2).

The Assessment data base is extremely low compared to Long and Turner (1975), but reflects Webber's (1977) results accurately (appendix 1.21). Understory production estimates for CC1 in comparison to CC2 reveal a possible inaccuracy in how the ID teams viewed forage production in relation to these two forest CCs. To go from a nonstocked state (CC1) to one where seedlings have become established (CC2) has no significant detrimental effect on actual forage production under most conditions. In fact, where shrubs dominate the understory, forage biomass actually peaks from 5 to 30 years after timber harvest (Hedrick et al. 1968). In other words, the biggest loss in forage production generally comes between CC3 and CC4. However, of the forested PNCs evaluated in this report, only one (PNC 5: mixed conifer) followed such a pattern.

The cedar-hemlock zone in the northern Rockies (PNC 12) is synecologically similar to PNC 2 (Daubenmire 1943). Both are characterized by the same climax and similar seral trees species, and most understory unions are dominated by tall shrubs. Therefore, forage production would also be expected to be reasonably comparable. For example, Eissenstat and Mitchell (1983) measured understory biomass on a northern Idaho clearcut two years after harvest (CC1 or 2; seedlings had been planted the previous year), both under natural vegetation establishment and following seeding with a grass mixture of orchard grass and timothy. Peak biomass on the control plots averaged 2,300–2,500 lb/acre both on slope sites (PC = 2–3) and bottomland (PC1), most of it in the form of thistles and annuals. On the grass treatment, production was unchanged on slopes, but had increased to 3,100 lb/acre on bottomland. In all cases except the bottomland seeding, shrubs showed signs of rapid growth, likely leading to their prevalence in 4 to 6 years at biomass levels not unlike that reported for Cascade forests (Long and Turner 1975).

Forage production estimates for PNCs 2 and 12, however, are neither similar nor consistent. In general, estimates for PNC 12 are 50% higher than those for PNC 2. In addition, the biggest drop-off between CC is between CC1 and CC2 within PNC 2, and between CC2 and CC3 within PNC 12.

Ponderosa Pine (PNCs 10, 17, and 18).—Ponderosa pine may be found in the western United States from Canada to Mexico. It is a dominant or codominant on six of Küchler's (1964) forested PNCs; mixed-conifer (PNC 5), western ponderosa (10), eastern ponderosa (15), Black Hills pine (16), pine-Douglas-fir (17), and Arizona pine (18). Understory vegetation associated with these PNCs is diversified, ranging from tall shrubs to sparse, herbaceous unions, and research has shown herbage yields to be, likewise, extremely variable.

Currie (1975) has reviewed the literature on ponderosa pine ranges in the central Rockies. He noted that, on sites with bunchgrass understory unions, annual forage production decreases from a maximum of 1,600 lb/acre on protected, open pastures (CC1 or 2), to 1,200 lb/acre on open pastures under moderate grazing, to 50 lb/acre on sites under dense timber. The Assessment data base (PNC 17) followed these values closely except for CC4, which was higher; i.e., 300 versus 50 lb/acre.

In northern Arizona (PNC 18), Pearson and Jameson (1967) depicted an inverse exponential relationship between herbage production and ponderosa pine basal area. On nonstocked stands (CC1), they estimated understory biomass at 600–700 lb/acre. For CC2, 3, and 4, their estimates were approximately 500, 250, and 50–100 lb/acre, respectively. Ffolliott and Clary (1974) also evaluated herbage production in PNC 18, and found it to be related not only to overstory, but to precipitation as well. For example, on nonstocked stands, understory biomass ranged from 500 lb/acre under 16 inches of precipitation (PC4) to over 1,000 lb/acre in the most mesic sites (PC1). Average production for all sites was about 750 lb/acre, which agreed with Pearson and Jameson's (1967) results.

Assessment forage production estimates for PNC 18 were incomplete, lacking entries for PC1 to CC1 and PC2 to CC1. Neverthless, the magnitude and trend of values that were available for CC1 followed the research results discussed above. Unfortunately, as shown several times previously on forested PNCs, the Assessment production estimates drop off more rapidly between CC1 and CC2 than relevant research indicates, and then remain mostly constant through CC4. The Assessment estimates were, consequently, much lower for CC2 and slightly high for CC4.

McConnell and Smith (1970) studied the response of understory to ponderosa pine thinning on an intermediately productive site (PNC 10, PC3) in eastern Washington. After 8 years, they estimated production under CC3 (20–60% percent pine canopy) to range from 250 to 500 lb/acre. Unthinned plots (CC4) produced about 75 lb/acre each year. The Assessment estimates for PNC 10 were characterized by the same improper response to CC as described for PNC 18.

Finally, in South Dakota's Black Hills (PNC 16), Pase (1958) examined herbage production in relation to overstory crown cover. He measured biomass in clearcuts (CC1) at 2,160 lb/acre, while under the densest stands (crown cover 70%) it had dropped to 40 lb/acre. Through interpolation of Pase's results understory

biomass for CC2 and CC3 was estimated at 1,360 and 300–500 lb/acre, respectively. Assessment (PNC 16) estimates were much lower than those of Pase for CC1 and CC2, but were higher for CC4; i.e., 1,000–1,200; 300–800; and 100–200 lb/acre, respectively. Again, production dropped too fast between CC1 and CC2, and leveled off too much for CC3 and CC4.

Pinyon-Juniper (PNC 21).—The pinyon-juniper type is widely distributed throughout the western United States. It is characterized by ecologically significant variations in precipitation and soils (Springfield 1976). Density of climax tree stands vary from dense stands of pinyon with essentially no understory to juniper savannas with excellent herbaceous cover. As a result, forage production varies widely, even within a given RU-ML combination. Jameson and Dodd (1969), for example, reported that potential forage production on soils derived from basalt, limestone, and some shales were 1,200–1,500; 600–1,200; and 500–800 lb/acre, respectively. Obviously, any attempt to integrate these variables into one estimator for the entire pinyon-juniper type would be a herculean task if it were to be based on scientific evidence.

Numerous authors (e.g., Arnold and Schroeder 1955, Jameson 1967, Pieper 1968, Clary 1971) have examined forage production within PNC 21, and their results, although variant, delineate production levels similar to those listed above (Jameson and Dodd 1969) for CC1, dropping off to 50–100 lb/acre for CC4. Such values are in remarkably close agreement with the ID-team's estimates for PNC 21 in the Assessment.

Oak-Hickory-Pine (PNC 101).—Conroy et al. (1982) recently investigated forage production on thinned loblolly pine plantations (Forest ML4 or 5) in the Virginia Piedmont, and developed a predictive model from their data. Forage biomass ranged from 1,500 lb/acre on open, moist sites (PC1, CC1) to 135 lb/acre in closed-canopied, xeric sites (PC4, CC4). The Assessment (PNC 101) estimates were reasonable for PC1–CC1, i.e., 1,200 lb/acre, but estimates for CC4 ranged no lower than 400 lb/acre. Unlike the situation with ponderosa pine, however, estimated production decreased in a nearly linear fashion across CC. The only problem was the large values for CC4.

Comparison With SCS Range Site Descriptions

When possible, each PNC was evaluated in comparison with SCS ecological or range sites, descriptions of which were taken from corresponding Major Land Resource Areas (MLRA). Assessment herbage and browse production estimates are listed in appendix 1 by PC and CC for each PNC. The SCS range forage production values, however, are based on climax communities, and can only be compared with Assessment estimates under CC1.

The SCS production estimates are presented in tabular form by PNC. Also included are dominant climax species, identified by acronyms or abbreviations (equivalent species names are provided in appendix 2), and estimates of annual peak forage biomass in normal years (lb/acre). Where range site production estimates consisted of three figures (production during favorable, normal, and unfavorable years), the one for normal years was used for comparison purposes. Where only two values were provided (favorable and unfavorable years), the average production between these two was used.

Nonforested Sites

Great Basin Sagebrush (PNC 32).—SCS estimates were taken from MLRA 28B (Central Nevada Basin and Range).

Range site	Dominant climax species	Normal peak biomass *lb/acre*
Sandy 8–12	Artrw, Stco, Orhy	600
Loamy 10–12	Artrw, Stth	840
Shallow Ca-loam 8–12	Ararn, Eula, Orhy	700
Steep loamy 8–12	Artrw, Stco, Orhy	400
Sandy 5–8	Atca, Eula, Orhy	300
Shallow Ca-slope 8–12	Ararn, Orhy, Stco	250
Loamy 5–8	Atco, Orhy, Stco	450
Clay basin 5–12	Atca, Agsm	1,800
Sodic loam 8–10	Artrw, Atco, Elci	400

The SCS production values tend to cluster around 450 lb/acre, which is equivalent to PC4 in the Assessment data base for PNC 32.

Only two out of nine SCS range sites produce more than 800 lb/acre. The average Assessment productivity class (PC2.5) interpolates to 1,000 lb/acre. Therefore, it appears that the Assessment estimates were somewhat inflated.

Saltbush-Greasewood (PNC 34).—SCS estimates were also taken from MLRA 28B (Central Nevada Basin and Range).

Range site	Dominant climax species	Normal peak biomass *lb/acre*
Sodic flat 5–12	Save, Atco, Spai, Dist	450
Sodic dunes 5–12	Save, Atco, Orhy	100
Alkali flat 8–10	Shar, Save, Elci	1,000
Sodic terrace 8–10	Save, Artrw, Elci	600

Except for PC4, which was a little high, comparable Assessment estimates for CC1 were reasonably close to these values.

California Steppe (PNC 41).—SCS estimates were taken from MLRAs 17 (Sacramento and San Joaquin Valley) and 18 (Sierra Nevada Foothills).

Range site	Dominant climax species	Normal peak biomass *lb/acre*
Coarse loamy	Brmo, Avfa, Tri., Erci	1,400
Loamy	Brmo, Avfa	1,000
Stony clay	Brmo, Avfa, Tri.	1,600
Sandy	Brmo, Avfa, Brri, Erci	700
Clayey	Brmo, Avfa, Erci, Lup.	4,200
Shallow loamy (17)	Brmo, Avfa, Erci	1,800
Shallow loamy (18)	Brmo, Avfa	800

The ranges of SCS total annual production and Assessment estimates were nearly congruent.

Grama-Galleta Steppe (PNC 47).—In Arizona, the SCS's MLRA 35 (Colorado and Green River Plateaus) contained several dozen range sites falling within the general description of PNC 47.

Range site	Dominant climax species	Normal peak biomass (Precipitation, inches)	
		6–10	10–14
		lb/acre	
Clay bottom	Spai, Bogr, Hija, Atca	2,500	3,000
Clay fan	Bogr, Orhy, Bohi, Atca	500	650
Clay-loam upland	Bogr, Spai, Bocu, Hija	650	650
Sandstone upland	Bohi, Hija, Bocu, Bogr	350	500
Sandy upland	Orhy, Stco, Sihy, Arfi	500	525
Saline bottom	Spai, Hija, Poab, Atca	1,100	—
Shale upland	Spai, Hija, Atco	150	—
Breaks	Pofe, Stco, Orhy, P–J	—	800
Loamy bottom	Agsm, Pofe, Orhy, Bogr, Atca	1,600	1,700
Cinder hills	Bocu, Bohi, Bogr, Hija	—	800

Assessment estimates were much lower than SCS observations for PNC 47. The maximum production shown (PC1, CC1, ML = D) of 600 lb/acre did not reach the median production from all SCS sites of 650 lb/acre.

Sagebrush Steppe (PNC 49).—Within five MLRAs (10, Upper Snake River Lava Plains; 11, Snake River Plains; 12, Lost River Valley; 13, Eastern Idaho Plateau; 25, Owyhee High Plateau of Idaho) the SCS has defined over 100 range sites that fall within PNC 49. Total production ranged from 125 (Very Shallow 8–16 inches precipitation, Arri/Pose) to 2600 lb/acre (Loamy 22" inches precipitation +, Artrv/Brca, Feid). The median production for all site was 700 lb/acre.

The Assessment estimates (CC1) for PNC 49 were adequate for PC1 and PC2; however, they appeared to be high for PC3 and PC4 (appendix 1.5). Nearly 75% of the SCS range sites produced less 1,000 lb/acre (CC3), while one-quarter of them produced less than 500 lb/acre (CC4). Apparently, more sensitivity was required in the range of 300–800 lb/acre and less in the range of 1,000–1,500 lb/acre.

Grama-Tabosa Shrubsteppe (PNC 52).—SCS range sites were taken from MLRA 41 (Southeastern Arizona Basin and Range).

Range site	Dominant climax species	Normal peak biomass *lb/acre*
Loamy upland 16–20	Bocu, Bogr, Opunt., Yucca	1,350
Limy slopes 16–20	Boer, Bocu, Yuba	1,200
Breaks 7–12	Himu, Ladi, Atco	150
Clay bottom 7–12	Himu, Anba	1,000
Clay upland 7–12	Himu, Boer, Opunt.	600
Granitic hills 7–12	Bogr, Boer, Yucca	700
Limy slopes 7–12	Boer, Himu, Latr	350
Limy upland 7–12	Mupo, Boer, Latr	250
Loamy bottom 7–12	Spwr, Himu, Bocu	2,000
Loamy upland 7–12	Boer, Himu, Bocu	750
Saline bottom 7–12	Spai, Himu, Atca	700
Basalt hills 12–16	Boer, Bocu, Agave	525
Clay upland 12–16	Himu, Bocu	950

Potential production (CC1) extended from 150 lb/acre on dry breaks to 2,000 lb/acre on loamy bottoms. The Assessment estimates in this case were tightly bunched at the low end of the scale, and apparently did not reflect the fairly wide range in SCS production values for PNC 52.

Trans-Pecos Shrub Savanna (PNC 53).—SCS range site descriptions were taken from MRLA 42 (Southern Desertic Basins, Plains, and Mountains) in Texas.

Range site	Dominant climax species	Normal peak biomass *lb/acre*
Clay flat	Himu, Paob, Spai	550
Draw	Mupo, Bocu, numerous shrubs	850
Gravelly	Latr, Boer, Mupo	250
Gravelly outwash	Acacia, Boer, Bocu	350
Gyp	Atca, Boer, Spai	300
Limestone hill and mountain	Krame., Boer	550
Loamy	Bogr, Boer, Scbr	800
Loamy bottomland	Spgi, Spai, Flce	1,500
Salty	Spai, Atca	700
Sand hill	Sporo., Atca, Latr	300

The Assessment estimates were weighted too high according to the SCS information. For example, "normal"

production for all but one of the above range sites fall below the Assessment estimate for PC3, and nearly half are less than the estimate for PC4.

Mesquite-Acacia Savanna (PNC 54).—According to maps of PNCs (USDA Forest Service 1978) and MLRAs (USDA SCS 1981), PNC 54 extends from the Rio Grande Plain into the Edwards Plateau. The assumption was made that the Rio Grande Plain more closely represented a mesquite-acacia savanna, and it was selected (MLRA 83) for this comparison.

Range site	Dominant climax species	Normal peak biomass
		lb/acre
Clay flat	Trich., Paob, Andro.	4,200
Clay loam	Trich., Andro., Prju	3,500
Deep sand	Ansc, Quer.	3,200
Loamy sand	Andro., Pasp., Quvi, Prju	3,500
Sandstone hills	Ansc, Sonu, Quer.	2,500
Sandy	Anli, Sonu, Prju	3,500
Shallow	Bocu, Cepa	2,200
Shallow ridge	Bocu, Ansc, Coleo.	1,800
Tight sandy loam	Trich., Ansc, Prju	3,000

In examining CC1 of PNC 54, it appears that its range of biomass is both too narrow and shifted somewhat to the low side. All of the range sites except one produce more than the 2,000 lb/acre stipulated in PC2. Peak biomass for two-thirds of the SCS range sites exceed the Assessment maximum in PC1-CC1.

Foothills Prairie (PNC 56).—The SCS range site descriptions were taken from a series entitled Foothills and Mountains. Although not referenced to a MLRA, they undoubtably fit MRLA 46 (Northern Rocky Mountain Foothills).

Range site	Dominant climax species	Normal peak biomass (Precipitation, inches)	
		6–10	10–14
		lb/acre	
Very Shallow	Agsp, Stco, Erio	600	800
Clayey	Agsp, Agsm, Pofr	1,300	2,000
Silty	Agsp, Fesc, Artr	1,500	2,200
Overflow	Elci, Agsm, Prun	2,500	3,300
Sandy	Agsp, Stco, Rhtr	1,600	2,300
Thin hilly	Agsp, Agsm, Artr	1,100	1,700
Sands	Calo, Orhy, Stco	2,000	—
Saline lowland	Spai, Elci, Atga	2,800	—

The Assessment data base effectively captured the lower (PC4) end of the forage production scale; and it can be considered reasonably accurate at the upper end (PC1) if the sites receiving additional runoff are not considered. Given the rarity of these sites, such an omission was probably not important.

Grama-Needlegrass-Wheatgrass (PNC 57).—PNC 57 spans two major MLRAs (52, Brown Glaciated Plain; 58, Northern High Plain). Fortunately, similarly named sites in both have the same production values.

Range site	Dominant climax species	Normal peak biomass
		lb/acre
Dense clay	Agsm, Stvi	900
Shallow	Agsp, Agsm, Bogr	900
Very shallow	Agro., Stco, Bogr	600
Saline upland	Spai, Agsm	500
Shale	Agsm, Spai, Dist	400
Clayey	Agsm, Stvi, Agsp	1,300
Silty	Agsp, Agsm, Stco	1,500
Sands	Spai, Orhy, Stco	2,000
Overflow	Elci, Agsm, Stvi	2,500

As with the foothills prairie (PNC 56), Assessment production estimates adequately span the appropriate SCS figures for PNC 57 only if those sites receiving additional water are not included.

Grama-Buffalo Grass (PNC 58).—PNC 58, one of the more widespread of all PNCs, encompasses the high plains from southeastern Wyoming to west Texas. Two major MLRAs were used, one in Colorado (67, Central High Plains) and the other in Texas (77, Southern High Plains). Those listed below are from MRLA 67; those from MRLA 77 fell in the same production range.

Range site	Dominant climax species	Normal peak biomass
		lb/acre
Loamy slopes	Bogr, Agsm	1,000
Siltstone plains	Bogr, Agsm, Atca	1,400
Sandy plains	Bogr, Calo, Bocu	1,800
Shaly plains	Spai, Bogr, Bocu	550
Plains swale	Agsm, Buda, Bogr	1,200
Salt flat	Spai, Bogr, Hija	1,000
Shallow siltstone	Bogr, Agsm, Eula	800
Sandstone breaks	Bogr, Bocu	750
Overflow	Pavi, Agsm, Bogr	2,500

Unlike the previous two PNCs, Assessment estimates for PNC 58 did not cover all SCS range sites, even when those receiving supplemental water, such as subirrigated and overflow sites, were excluded. The Assessment estimates were lower for all PCs.

Wheatgrass-Needlegrass (PNC 59).—SCS range site descriptions were taken from two sets of MLRAs in South Dakota: the Prairie Shale Plains and Badlands (60A) and, to its east, the more mesic Northern Rolling Pierre Shale Plains (63A).

Range site	Dominant climax species	Normal peak biomass (MLRA) 60	63
		lb/acre	
Loamy overflow	Ange, Pavi, Agsm, Rosa	2,600	3,200
Loamy terrace	Agsm, Stvi, Calo	2,300	2,700
Sands	Ansc, Anha, Calo, Stco	2,000	2,400
Silty	Agsm, Stvi, Stco	1,850	2,250
Clayey	Agsm, Stvi, Buda	1,750	2,050
Thin upland	Stco, Bogr, Cafi, Agsm	1,400	1,750
Shallow to gravel	Stco, Bogr, Cafi	1,150	1,450
Thin claypan	Bogr, Buda, Agsm	850	1,050
Saline upland	Agsm, Dist, Atga	750	—

The Assessment estimates fit these SCS averages reasonably well; however, it appears that the fit might have been better if they were shifted upward as a group by a few hundred pounds per acre.

Wheatgrass-Bluestem-Needlegrass (PNC 60).—SCS range site descriptions were taken from MLRA 55 (Black Glaciated Plains), found in east-central North Dakota and South Dakota.

Range site	Dominant climax species	Normal peak biomass *lb/acre*
Subirrigated	Ange, Pavi, Sonu	5,100
Overflow	Ange, Stvi, Agsm	3,850
Saline lowland	Agsm, Dist, Puai	3,750
Sands	Anha, Calo, Ansc, Stco	2,800
Silty	Stvi, Agsm, Stco, Ansc	2,800
Clayey	Agsm, Stvi, Ansc	2,600
Thin upland	Ansc, Stvi, Stco	2,350
Claypan	Agsm, Stvi, Bogr	2,000
Thin claypan	Agsm, Bogr, Buda	1,450
Very shallow	Stco, Bogr, Cafi	1,450

A comparison of the above measures with the Assessment leads to the same conclusion reached several times before; i.e., the two are reasonably congruous only if those sites receiving supplemental water through runoff or subirrigation are neglected.

Bluestem-Grama Prairie (PNC 62).—The SCS range site descriptions were taken from the 20- to 24-inch precipitation zone in west-central Kansas. They are not yet associated with MLRAs; however, if they were, MLRA 73 (Rolling Plains and Breaks) would probably apply best.

Range site	Dominant climax species	Normal peak biomass *lb/acre*
Blue shale	Bocu, Agsm, Ange	1,800
Chalk flats	Ansc, Bocu	3,000
Clay lowland	Pavi, Ange, Sonu	4,500
Clay upland	Bocu, Agsm, Spas	2,000
Gravelly hills	Ange, Anha, Bocu	1,600
Limy upland	Ange, Bocu, Ansc	2,450
Loamy terrace	Pavi, Ange, Sonu	3,500
Saline subirrigated	Spai, Pavi, Sonu	6,500
Sandy	Anha, Ange, Ansc	2,200
Loamy lowland	Ange, Sonu, Ansc	4,800
Red shale	Ange, Ansc, Bocu	1,200

Although the Assessment data base adequately covered the unproductive end of range sites (PC4), it was somewhat low for productive ones. In fact, nearly half of the SCS range sites in good to excellent condition produce more than the Assessment estimate for PC1 (3,000 lb/acre).

Bluestem Prairie (PNC 66).—The SCS sites for PNC 66 were taken from MLRA 76 (Bluestem Hills) in east-central Kansas.

Range site	Dominant climax species	Normal peak biomass *lb/acre*
Clay lowland	Sppe, Pavi, Ange	5,000–7,500[2]
Clay upland	Ange, Ansc, Sonu, Pavi	2,500–2,500
Claypan	Ange, Ansc, Bocu	2,000–3,000
Flint ridge	Ansc, Ange, Bocu	1,500–2,200
Loamy lowland	Ange, Sonu, Pavi	6,000–8,000
Loamy upland	Ange, Ansc, Sonu, Pavi	3,500–5,000
Shallow limy	Ansc, Bocu	2,000–2,500

The Assessment estimates did an excellent job of covering both the range and distribution of SCS range sites examined.

Nebraska Sandhills (PNC 67).—SCS range site information was taken from MLRA 65 (Nebraska Sandhills). Because of its unique physiography and vegetation, the correlation between Küchler PNC and MLRA is nowhere higher than for the Nebraska sandhills.

[2]*Use of fire and plant vigor influence production among sampling areas in the same ecological condition. For this study, the higher values would reflect a more intensive level of range management (ML = D)*

Range site	Dominant climax species	Normal peak biomass (Precipitation, inches)	
		6–10	10–14
		lb/acre	
Subirrigated	Ange, Sonu, Ansc, Sppe	4,400	4,900
Sandy lowland	Ansc, Anha, Calo, Pavi	2,400	2,900
Savanna	Ansc, Stco, Calo, Pipo	2,000	—
Sandy	Calo, Anha, Ansc, Stco	2,400	2,900
Choppy sands	Anha, Calo, Ansc, Pavi	2,200	2,700
Sands	Anha, Calo, Ansc, Pavi	2,300	2,800
Shallow to gravel	Bogr, Anha, Stco, Spcr	1,000	1,300

Except for those sites that either receive supplemental water or are excessively xeric, total production varies between 2,000 and 3,000 lb/acre. The Assessment estimates did a reasonable job of depicting these figures. It could be argued that PC1 underestimated the most productive sites, and PC2 overestimated the top of the 2,000–3,000 lb/acre range; however, such inaccuracies are insignificant at a national level of integration.

Cross Timbers (PNC 75).—SCS range site information for PNC 75 were obtained from MLRA 84 (Cross Timbers) in Oklahoma and Texas. The dominant species, listed below, do not contain woody species prevalent in the Cross Timbers, which usually present a savanna-like physiognomy. Among the woody species mentioned in the range site descriptions as being common in the Cross Timbers region are *Quercus marilandica, Q. stellata, Rhus* spp., *Carya illinvensis,* and *Ulmus* spp.

Range site	Dominant climax species	Normal peak biomass
		lb/acre
Deep sand savanna	Anha, Ansc	3,000
Deep sand savannah breaks	Sonu, Ange	2,600
Eroded clay	Bocu, Bogr	1,500
Eroded sandy savanna	Ansc, Sonu	2,100
Eroded shallow savanna	Ansc, Sonu, Pavi	1,400
Heavy bottomland	Pavi, Sppe, Ange	5,500
Loamy bottomland	Ange, Pavi, Sonu	6,500
Sandy bottomland	Anha, Sonu, Ansc	2,900
Sandstone hills	Ansc, Sonu, Ange	2,800
Sandy	Ansc, Sonu, Pavi	3,700
Sandy savanna	Anha, Ansc	4,000
Savannah breaks	Ange, Ansc, Sonu	1,200
Shallow savanna	Ansc, Anha, Bocu	2,100
Subirrigated	Pavi, Ange, Sonu	9,000

The Assessment data base came well short of correctly estimating peak biomass on the most productive sites (PC1), even if the subirrigated site was not considered. In addition, its lowest estimates (PC4) were too high for several of the eroded SCS range sites. In other words, actual Cross Timbers understory production extends below the Assessment estimates at the low end of the range and above it at the high end.

Mesquite-Buffalo Grass (PNC 76).—For PNC 76, SCS range site information was taken primarily from MLRA 78, the Central Rolling Red Plains of Texas. Additional production figures were obtained from MLRA 80, the Texas Central Prairie, which also is included in PNC 76; hence, the range in biomass for some range sites shown below.

Range site	Dominant climax species	Normal peak biomass
		lb/acre
Clay loam	Bogr, Buda, Himu	1,500
Clay flat	Himu, Spai, Buda	1,000–1,600
Claypan prairie	Paob, Bocu, Buda	2,100
Claw	Bocu, Paob, Agsm	3,200
Gravelly	Bocu, Ansc, Bohi	1,000–1,500
Gyp	Bocu, Ansc, Buda	600
Loamy bottomland	Sonu, Pavi, Bocu	2,700–5,500
Loamy prairie	Bogr, Buda, Bocu	1,800–2,200
Loamy sand	Anha, Ansc, Bocu	2,300–4,500
Rough breaks	Bocu, Ansc, Bohi	600
Sandy loam	Bogr, Bocu, Paob	2,200–4,200
Shallow clay	Bogr, Bocu, Buda, Himu	1,100–1,500
Very shallow	Bocu, Ansc, Buda	800

Numerous woody species were recorded by the SCS as being associated with these range sites; however, their cover seldom exceeded 5% under excellent condition. Among species prevalent to the Rolling Red Plains are *Ephedra* spp., *Celtis* spp., *Juniperus* spp., *Lycium* spp., *Condalia lycioides,* and *Acacia greggii.* Mesquite (*Prosopis* spp.) is normally not a climax constituent, but increases greatly during retrogression, according to the SCS range site descriptions.

The Assessment estimates for PNC 76 encompassed all range sites except the most productive (loamy bottomland) and the least productive (gyp, rough breaks, very shallow). The SCS range sites in PNC 76 showed comparatively wide variation in production depending mostly upon precipitation, and the ID-team estimates could have been expanded in range to accommodate these extremes.

Juniper-Oak Savanna (PNC 77).—The juniper-oak savanna is superimposed mostly on the Edwards Plateau region of Texas (MLRA 81). Like the previous PNC, mesquite-buffalo grass (PNC 76), the Edwards Plateau is characterized by a savanna composed of numerous tree species that rarely exceed 5% in total crown cover. Many of the woody species are common to both PNCs. As in PNC 76, mesquite only becomes dominant during retrogression.

Range site	Dominant climax species	Normal peak biomass (Precipitation, inches) 6–10	10–14
		lb/acre	
Clay loam	Bocu, Andro., Buda	2,700	—
Deep redland	Ansc, Sonu, Bocu	—	3,800
Flagstone	Bocu, Ledu	800	—
Loamy bottomland	Sonu, Ansc, Bocu, Ange	3,200	4,500
Low stony hill	Andro., Bocu, Ledu	1,800	2,300
Shallow	Bocu, Ansc, Buda	1,900	2,400
Shallow ridge	Bocu, Ledu, Sema	1,500	—
Steep rocky	Ansc, Bocu, Ledu	1,300	—
Steep adobe	Ansc, Sonu, Bocu	—	2,000

Taken collectively, the Assessment estimates for PNC 77 were relatively high. In fact, more than half of the SCS range sites fall below the production estimate for PC4, some by 50% or more. Alternatively, none of the range sites reach the magnitude of PC2, let alone approaching that for PC1.

Mountain Meadow (PNC 107).—Mountain meadows are not associated with any specific MLRAs, but are interspersed throughout the western cordilleran forests. As such, SCS descriptions of most meadow sites can be found in MLRAs comprising the Rocky Mountain Range and Forest Land Resource Region (USDA SCS 1981). For this evaluation, meadow sites have been taken from Idaho and Colorado.

Range site	Dominant climax species	Normal peak biomass *lb/acre*
Idaho		
Semiwet meadow, north	Deca, Carex Agtr	3,800
Semiwet meadow, south	Carex, Agtr, Deca	2,250
Semiwet saline meadow	Spai, Poju, Dist	1,750
Wet meadow, north	Carex, Deca, Junc.	6,000
Wet meadow, south	Carex, Junc.	5,000
Colorado		
Swale meadow	Agsm, Cane, Elci	2,000
Salt meadow	Spai, Dist, Agsm	1,500
Wet meadow	Deca, Cane, Agtr	2,000[3]

[3]*Some SCS range conservationists believe this figure should be higher, perhaps 3500–4000 lb/acre. (Personal communication with Noel Wellborn, SCS-Colorado.)*

For the most part, the Assessment estimates adequately reflected SCS range site production figures. They could have been made more accurate by raising PC1 by 2,000 lb/acre and PC4 by 500 lb/acre.

Forested Sites

SCS site descriptions are generally only available for western PNCs, and of these, some include no understory production information. For example, Oregon has developed range site descriptions for associations in the cedar-hemlock zone (PNC 2); however, they contain blanks in the sections referring to both understory production and suggested initial stocking rates. Those PNCs for which information is available follow.

Western Ponderosa Forest (PNC 10).—Although PNC 10 is widespread throughout Washington, Oregon, Idaho, and western Montana, few range site descriptions that include production information have been written for it. The following were taken from Washington (MLRA 6, Cascade Mountains Eastern Slope; MLRA 9, Palouse and Nez Perce Prairies).

Range site	Dominant climax species	Normal peak biomass (Canopy cover, % 0–20	20–40	40+
		lb/acre		
Loamy, ponderosa pine, Idaho fescue	Feid, Agsp, Basa	1,200	900	300
Very stony, shallow, ponderosa pine, bluebunch wheatgrass	Agsp, Pose, Feid, Syal	600	400	150
Loamy, 20–45, droughty	Cage, Caru, Lup., Syal	—	110	—

The Assessment estimates were inadequate to express the range of understory production shown in only three SCS range site descriptions.

Although a constant figure of 800 lb/acre across all PCs may have approximated the average of all sites, it certainly did not mimic their variation. In addition, two of the SCS range sites relate understory biomass to overstory canopy (i.e., CC); they depict an attenuation from CC1 to CC4 of about 4:1, with most of the decrease between CC3 and CC4. Contradictorily, the Assessment estimates show an astounding 8:1 reduction between CC1 and CC2, followed by a gradual increase in understory production in CC3 and CC4. There is no logical explanation for the conceptual model of understory production represented in the Assessment estimates.

Douglas-fir Forest (PNC 11).—SCS site descriptions of Douglas-fir associations are only available from Idaho. As shown with ponderosa pine, few SCS state offices have developed descriptions, including understory production information, for the more mesic coniferous forest zones.

Range site	Dominant climax species	Normal peak biomass (50% canopy) lb/acre
Douglas-fir, stony 22	Caru, Feid, Artrv	1,000
Douglas-fir, mountain snowberry, 22+	Agsp, Syor, Artrv	900

The SCS information is insufficient to judge the scope of the Assessment for PNC 11. The values shown above, assuming 50% canopy cover is equivalent to CC3, fall nicely in the range of appropriate Assessment estimates; however, that is the only conclusion possible.

Pinyon-Juniper (PNC 21).—The SCS range site information was taken from two states, Utah and New Mexico. The sites represent six MLRAs in Utah and two other MLRAs in New Mexico. Obviously, pinyon-juniper is widely distributed both geographically and ecologically within the intermountain and southern Rocky Mountain regions.

Range site	Dominant climax species	Normal peak biomass lb/acre
Utah		
Upland shallow loam	Agsp, Orhy, Juos	1,300
Upland shallow loam (summer ppt)	Carex, Orhy, Bogr, Juos	750
Upland stony loam	Agsp, Pofe, Juos	1,000
Upland stony loam (summer ppt)	Orhy, Pone, Juos Pied	1,600
Shallow upland stony sand	Stco, Bogr, Spcr, Juos, Pied	850
Upland shallow hardpan	Orhy, Stco, Juos, Pied	650
Semidesert shallow loam (summer ppt)	Muem, Pied, Juos	325
New Mexico		
Sand plains	Orhy, Sporo., Jumo, Peid	800
Shallow savanna	Stco, Bogr, Hija, Jusc, Pied	600
Hills	Bogr, Ansc, Bocu, P–J	1,100
Shallow sandstone	Bogr, Bocu, P–J	750
Breaks	Bocu, Ansc, P–J	800
Shallow limy savanna	Ansc, Bocu, P–J	700
Deep sand savanna	Andro., Calo, P–J	1,000

The Assessment estimates adequately covered most of the SCS range site production figures. If the estimate for CC1 (1,000 lb/acre) were increased by 50%, coverage would have been more than adequate.

California Oakwoods (PNC 26).—The SCS estimates were obtained from MLRA 15, Central California Coast Range; and 18, Sierra Nevada Foothills.

Range site	Dominant climax species	Normal peak biomass lb/acre
Blue oak-white oak	Qudo, Qulo, Brmo, Avfa	
Open canopy (CC1)		2,000
Medium canopy (CC3)		1,200
Dense canopy (CC4)		600
Gravelly loam (ML=D)	Brmo, Avfa	1,200
Very stony shallow loam	Qudo, Brmo, Feme	400
Very gravelly loamy	Brmo, Avfa, Erci, Qudo	900
Claypan	Brmo, Erci, Qudo	2,100

If the SCS production figures are accurate, the Assessment estimates contained two serious shortcomings. First, they did not mimic the decreased production associated with overstory canopy closure (i.e., increasing CC). Second, they came nowhere near approaching the range in production (400–2,100 lb/acre) associated with CC1.

DISCUSSION

Herbage and browse production estimates for major rangeland PNCs in the 1980 Assessment varied in accuracy, both overall and in relation to changes in PC and CC. The following discussion attempts to synthesize results from each of the evaluation techniques (intrinsic evaluation and comparisons with both research information and SCS range sites) for those PNCs that appeared to have deficiencies.

One aspect concerning the assumptions made by the Assessment ID teams became important during the synthesis of results reported above. Küchler's (1964) PNCs were mapped on a scale of 1:7,500,000. At this scale, a map distance of only 1 mm would amount to 7.5 km (4.7 miles) on the ground. Therefore, Küchler could not include the mosaic of natural associations that are present across the landscape within any given PNC, but mapped only generalized vegetation. It is probably safe to assume that the extent of Küchler's PNCs roughly coincide with the geographic range of their respective dominant species as such species comprise climatic climax communities, i.e., are found on zonal soils (Personal Communication, Robert G. Bailey, USDA Forest Service, Fort Collins, Colo.).

Given this situation, the ID teams had to decide whether or not to include resource outputs from all associations making up a "significant" proportion of the land area within a given PNC, even if they are not normally a climatic component of the PNC. Their decision would have consitituted a crucial assumption built into their inituitive models. For example, on the short-grass plains (PNC 58), communities more typical of the mixed-grass and tall grass prairie occur on bottomland sites, sometimes over extensive areas. Obviously, such com-

munities are capable of producing much more herbage than any site dominated by blue grama and buffalo grass, the characteristic species of PNC 58. Therefore, the assumption to include these communities would greatly affect the Assessment estimates for PC1 within several PNCs.

Evidently, the intent of the ID teams was to view each PNC as a homogeneous abstraction (personal communication, Richard Ross, Superior National Forest, Duluth, Minn.). Whether or not individual ID teams followed such a strategy is unclear, given the range of production estimates for some PNCs and the lack of data for "abstract" communities.

Sagebrush-Grass Region (PNC 32 and 49).—All three methods provided results consistent with each other. Assessment production estimates for the 140 to 170 million acres (Tisdale and Hironaka 1981) of sagebrush-grass in the western United States were too high, primarily because of the conceptual model of production in relation to CC used by the ID team(s). First and most important, Assessment production estimates were unaffected by decreasing CC, so areas in less than excellent range condition would therefore be shown to have the same production as those in excellent condition (table 8). Although no one knows how much sagebrush-grass rangeland is in depleted condition, there is some indication that three-fourths of it is rated in fair condition or worse and about one-third may be in poor condition (USDA BLM 1977). Even if these figures are exaggerated, the proportions must still be significantly large.

The second shortcoming of the Assessment estimates lies in their overestimation of production on sites with lower production potential (PC3, PC4). Most of the sagebrush-steppe (PNC 49) is characterized by sagebrush-grass communities dominated by *Artemisia tridentata* spp. *wyomingensis*. These communities normally produce substantially less than the Assessment estimates provided under PC3 and PC4, as explained previously in this paper.

Grama-Galleta Steppe (PNC 47).—The Assessment estimates for PNC 47 constituted a paradox. According to the SCS range site descriptions, they greatly underestimated production on ranges in good condition (CC1). However, because the conceptual model developed by the ID team called for constant production across all CCs within a given PC, it is quite possible that Assessment estimates for the lower CCs were reasonably accurate. Unfortunately, little, if any, research has been published on total production for this PNC. Initially, the Assessment estimates could be improved by progressively raising the values in the higher CCs by fourfold to fivefold.

Grama-Tabosa Shrubsteppe (PNC 52).—The same general comments made concerning PNC 47 apply to PNC 52; i.e., the conceptual model of production versus CC was constant, and the Assessment estimates underestimated production at the higher CCs. The remedy, changing the conceptual model, remains the same.

Trans-Pecos Shrub Savanna (PNC 53).—The Assessment estimates apparently were consistently high across the board. They were relatively precise in relation to each other, but inaccurate. The conceptual model could be changed by eliminating or greatly lowering the intercept (α_0) in order to remedy this discrepancy. Other more subtle changes to the model may also be useful, depending upon the availability of future research information.

Mesquite-Acacia Savanna (PNC 54).—The Assessment estimates for PNC 54 were, in contrast to PNC 53, consistently low across the board. The conceptual model expressed in the ID-team estimates contained an excessive number of interaction effects for the available information, and its intercept (PC4–CC4) appeared too low. A simpler model reflecting the wide range in potential production would be both more accurate and easier to interpret.

Grama-Buffalo Grass (PNC 58).—Information about PNC 58 illustrates the problem of which associations or range sites to include in the evaluation, discussed earlier in this section. According to comparisons with research data available from shortgrass sites, the Assessment estimates overestimated actual production. On the other hand, when compared to descriptions of all important SCS range sites comprising PNC 58, the Assessment estimates fell well short. A solution to this paradox, and the resultant improvement of any Assessment estimates for PNC 58, can only come after the underlying assumption is made explicit, one way or the other. Given the constraint of accounting for land area by PNCs as they are mapped, it appears that the Assessment estimates actually underestimate herbage production at all PCs.

Cross Timbers (PNC 75).—Inadequacies in the Assessment estimates of PNC 75 were discussed in the section on comparisons with SCS range site descriptions. The lack of coverage may have been due in part to ID-team unfamiliarity with characteristics of the Cross Timbers. Unlike major PNCs of the Great Plains, the Cross Timbers has received less research or publicity since the early work of Dyksterhuis (1948). Such a situation points out the importance of adequate background information if intuitive models are to be effective. The problem may have been a causal factor in discrepancies between Assessment estimates and SCS range site descriptions for other PNCs restricted primarily to the southern Plains, either to a small (PNC 76) or larger (PNC 77) extent.

Forested PNCs (2, 5, 10, 11, 14, 26, 91, 95, 101, 102, 103).—Because of the lack of research data and range site descriptions for forested PNCs, a synthetical evaluation of Assessment estimates is infeasible. The only other evaluation possible, that of examining the Assessment estimates intrinsically, has already been completed in this paper.

CONCLUSIONS

Intuitive models, like other models used in ecology and natural resource management, are intrinsically transient in nature. They are developed for a specific purpose, but seldom are used by others who may have

similar but (always) different needs. Some of the reasons for the non-use of existing models has to do with their applicability to related problems for which they were not designed. Just as important, however, is the idea that much of the usefulness derived from modeling comes from activities associated with model development (Innis 1972).

For RPA Assessments, the problem is not one of different users, but of the same user over time. Consequently, unless legislation or regulations pertaining to recurring Assessments are amended, the users' needs are unchanged, and one of the major reasons for not using existing models is eliminated.

Looking into the future 10 to 15 years, one sees little likelihood of replacing the intuitive models of herbage and browse production used in the 1980 Assessment with more quantitative mathematical models. The major impediment to developing such regional level models is the lack of a quantititive theoretical framework in ecology (Joyce et al. 1983).

Given the continued raison d'etre of RPA Assessments, the lack of a quantitative approach towards providing herbage and browse production coefficients at the regional level, and the overall accuracy of ID-team estimates in the 1980 Assessment, one can conclude that such estimates can provide the framework for intuitive primary models in the next Assessment. Nonetheless, it seems reasonable to suggest that some parts of the Assessment data set are sufficiently inaccurate to require changing. If such an undertaking is attempted, a procedure like that used in this paper should be adopted. In addition, future ID-teams would be well advised to more adequately record assumptions made that affect their estimates of resource outputs, both for their own edification and internal consistency, and as an aid in appraising the outputs of their intuitive models.

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APPENDIX 1

Herbage-Browse Production Estimates (lb/acre) by Productivity Class, Condition Class, and Management Level (ML) for Selected PNCs in the 1980 Assessment Range Data Base

NONFORESTED SITES

PNC 32: Great Basin Sagebrush
Owner – 2
State – NV

Condition Class	Productivity Class 1	2	3	4
1	1500	1200	800	400
	1500	1200	800	400
2	1500	1200	800	400
	1500	1200	800	400 (D)
3	1500	1200		400
	1500	1200	800	400 (D)
4	1500	1200		400
	1500	1200	800	400 (D)

ML A
ML C (D)

PNC 34: Saltbush-Greasewood
Owner – 2
State – UT

Condition Class	Productivity Class 1	2	3	4
1	1000	750	500	250
	1000	750	500	250
2	900	650	400	150
	900	650	400	150
3	800	550	300	50
	800	550	300	50
4	750	500	250	0
	740	500	250	0

ML A
ML C

PNC 41: California Steppe (Annual Grassland)
Owner – 4
State – CA

Condition Class	Productivity Class 1	2	3	4
1	3200	2800	1600	800
	4500	3700	1800	900
2	3200	2800	1600	800
	4500	3700	1800	900
3	3200	2800	1600	800
	4500	3700	1800	900
4	3200	2800	1600	800
	4500	3700	1800	900

ML C
ML D

PNC 47: Grama-Galleta Steppe
Owner – 4
State – NM

Condition Class	Productivity Class 1	2	3	4
1	500 600	400 500	300 300	200 200
2	500 600	400 500	300 300	200 200
3	500 600	400 500	300 300	200 200
4	500 500	400 500	300 300	200 200

ML B
ML D

PNC 49: Sagebrush Steppe
Owner – 2
State – ID

Condition Class	Productivity Class 1	2	3	4
1	2000 2500	1500 1800	1000 1200	500
2	2000 2500	1500 1800	1000 1200	500
3	2000 2200	1500 1600	1000 1200	500
4	2000 2200	1500 1600	1000 1100	500

ML C
ML D

PNC 52: Grama-Tabosa Shrubsteppe
Owner – 4
State – NM

Condition Class	Productivity Class 1	2	3	4
1	500	300	200	100
2	500	300	200	100
3	500	300	200	100
4	500	300	200	100

ML B, C

PNC 53: Trans-Pecos Shrub Savanna
Owner – 4
State – TX

Condition Class	Productivity Class 1	2	3	4
1	1700 2100		900 1200	500 500
2	1600 2000		800 1200	400 400

Condition Class	3	1400 2000		700 1200	300 300
	4	1200 2000		600 1200	200 200

ML C
ML D

PNC 54: Mesquite-Acacia Savanna
Owner – 4
State – TX

		Productivity Class			
		1	2	3	4
Condition Class	1	2500 2500	2000 2400	1500 1800	1000 1200
	2	1900 2400	1500 1900	1100 1400	700 900
	3	1200 1600	900 1200	700 1000	500 700
	4	500 700	400 600	300 400	200 300

ML B
ML E

PNC 56: Foothills Prairie
Owner – 4
State – MT

		Productivity Class			
		1	2	3	4
Condition Class	1	2000	1400	1000	500
	2	1500	1100	800	400 400
	3	1000	800	500	300 300
	4	500 500	400 400	300 300	200 200

ML A
ML C

PNC 57: Grama-Needlegrass-Wheatgrass
Owner – 4
State – MT

		Productivity Class			
		1	2	3	4
Condition Class	1	1600 1900	1200 1400	800 1000	400 500
	2	1200 1400	900 1100	600 800	300
	3	800 900	600 700	400	200
	4	400	300	200	100

ML B, C
ML D

PNC 58: Grama-Buffalo Grass
Owner – 2
State – CO

Condition Class	Productivity Class 1	2	3	4
1	1000	800	600	400
2	800	600	500	300
3	600	500	300	200
4	400	300	200	100

ML C

PNC 59: Wheatgrass-Needlegrass
Owner – 4
State– UT

Condition Class	Productivity Class 1	2	3	4
1	2500 3700	1700 2500	1000 1500	600 900
2	1700 2500	1300 1900	800 1200	400 600
3	1000 1500	800 1200	500 700	200 300
4	600 900	400 500	200 300	100 100

ML C
ML D

PNC 60: Wheatgrass-Bluestem-Needlegrass
Owner – 4
State – ND

Condition Class	Productivity Class 1	2	3	4
1	3000 3100	2400 2500	1800 1800	1200 1200
2	2500 2600	200 2100	1500 1500	1000 1000
3	2000 2200	1600 1800	1200 1300	800 900
4	1500 1600	1200 1300	900 1000	600 700

ML C
MLD

PNC 62: Bluestem-Grama Prairie
Owner – 4
State – KS

Condition Class	Productivity Class 1	2	3	4
1	3000 3000	2400 2400	1800 1800	1200 1200
2	2700 2700	2200 2200	1600 1600	1100 1100

Condition Class					
	3	2300 2800	1900 2300	1400 1700	900 1100
	4	2000 2400	1600 1900	1200 1400	800 1000

ML A, C
ML D

PNC 66: Bluestem Prairie
Owner – 4
State – OK

Condition Class	Productivity Class				
		1	2	3	4
	1	6800 7400	4400 5000	3000 3500	1700 2300
	2	6700 7200	4300 4800	2800 3300	1600 2100
	3	5500 6800	3800 4400	2600 3100	1400 1900
	4	5000 6800	3500 4400	2200 3100	1000 1900

ML C
ML D

PNC 67: Nebraska Sandhills
Owner – 4
State – NE

Condition Class	Productivity Class				
		1	2	3	4
	1	4300	3200	2100	1000
	2	4000	3100	2000	800
	3	3900	2800	1700	600
	4	3900	2800	1700	600

ML C

PNC 75: Cross Timbers
Owner – 4
State – OK

Condition Class	Productivity Class				
		1	2	3	4
	1	4800	3900	3000	2100
	2	4000	3200	2500	1700
	3	3200	2500	2000	1300
	4	2400	1800	1500	900

ML C

PNC 76: Mesquite-Buffalo Grass
Owner – 4
State – TX

Condition Class	Productivity Class				
		1	2	3	4
	1	3500 4200	2700 3200	2000 2000	1200 1200

	2	3400 4100	2600 2600	1900 1900	1100 1100
Condition Class	3	3200 3800	2500 3000	1700 1700	1000 1000
	4	3000 3600	2300 2800	1500 1500	800 800

ML B
ML D

PNC 77: Juniper-Oak Savanna
Owner – 4
State – TX

		Productivity Class			
		1	2	3	4
	1	6000	4800	3600	2400
	2	4800	3600	2400	1800
Condition Class	3	3600	2400	1800	1200
	4	4800	2400	1800	1200

ML D

PNC 107: Mountain Meadow
Owner – 1
State – MT

		Productivity Class			
		1	2	3	4
	1	4000 4500	3000 3400	2000 2200	1000 1100
	2	3600 4000	2600 3000	1600 1800	600 800
Condition Class	3	3200 3800	2200 2600	1200 1400	400 600
	4	3000 3500	2200 2400	1000 1200	200 400

ML C
ML D

PNC 2: Cedar-Hemlock-Douglas-fir Forest
Owner – 4
State – OR

		Productivity Class			
		1	2	3	4
	1	2000 4500	1700 3500	1500 2500	1500
	2	500 3500	500 3000	500 1500	400
Condition Class	3	100 100	100 100	100 100	50
	4	100 100	100 100	100 100	100

ML A5
ML D5

PNC 5: Mixed Conifer Forest
Owner – 4
State – CA

Condition Class	Productivity Class 1	2	3	4
1	6000	4500	2000	3000
2	5000	3800	1700	2500
3	1000	900	700	1300
4	400	400	600	1000

ML B

FORESTED SITES

PNC 10: Western Ponderosa Forst
Owner – 4
State – OR

Condition Class	Productivity Class 1	2	3	4
1	800 900	800 900	800 900	800 900
2	100 100	100 100	100 100	100 100
3	200 500	200 500	200 500	200 500
4	400 600	400 600	400 600	400 600

ML B3
ML D4

PNC 11: Douglas-fir Forest
Owner – 1
State – MT

Condition Class	Productivity Class 1	2	3	4
1	4000	4000	1700	500
2	2000	2000	900	300
3	1000	1000	500	200
4	700	700	500	100

ML B2, B3

PNC 14: Western Spruce-Fir Forest
Owner – 1
State – CO

Condition Class	Productivity Class 1	2	3	4
1	4200 4000	3000 3200	2200 2200	1200 1200
2	3000 3000	1500 2000	1000 1600	500 1000
3	1000 1600	400 1000	300 800	100 300
4	0 500	0 100	0 100	0 100

ML B3
ML C5

PNC 21: Pinyon-Juniper
Owner – 1
State – AZ

Condition Class	Productivity Class 1	2	3	4
1	900	700	500	200
	1200	1000	700	300
2	800	600	400	200
	1100	900	600	200
3	700	500	300	100
	1000	800	500	200
4	600	400	200	100
	800	700	400	100

ML B1
ML D1

PNC 26: California Oakwoods Forest
Owner – 4
State – CA

Condition Class	Productivity Class 1	2	3	4
1	2900	2900	2900	2900
	4200	4200	4200	4200
2	3200	3200	3200	3200
	4500	4500	4500	4500
3	3000	3000	3000	3000
	3600	3600	3600	3600
4	2900	2900	2900	2900
	3500	3500	3500	3500

ML B1
ML D1

PNC 91: Oak-Hickory Forest
Owner – 4
State – MD

Condition Class	Productivity Class 1	2	3	4
1	800	800	1000	1200
	400	400	1500	1500
2	300	300	400	600
	4000	4000	2000	1500
3	2000	2000	500	700
	4000	4000	2000	1500
4	300	300	300	300
	4000	4000	2000	1500

ML A1, A3
ML D3

PNC 95: Appalachian Oak Forest
Owner – 4
State – PA

		Productivity Class			
		1	2	3	4
Condition Class	1	800	800	700	600
	2	600	600	600	500
	3	500	500	500	500
	4	500	500	500	600

ML C2

PNC 101: Oak-Hickory-Pine Forest
Owner – 4
State – VA

		Productivity Class			
		1	2	3	4
Condition Class	1	1200	1200	1000	1000
	2	1000	1000	400	200
	3	600	700	500	600
	4	500	400	500	600

ML B3

PNC 102: Southern Mixed Forest
Owner – 4
State – FL

		Productivity Class			
		1	2	3	4
Condition Class	1	3000 750	2000 500	2000 500	1000
	2	2200 2200	1500 1500	1500 1500	800
	3	1200 1200	800 800	800 800	400
	4	1200 1500	800 1000	800 1000	400

ML A3
ML A6

PNC 103: Southern Floodplain Forest
Owner – 4
State – LA

		Productivity Class			
		1	2	3	4
Condition Class	1	1000 12000	1000 12000	800	300
	2	900 12000	900 12000	700	200
	3	200 12000	200 12000	200	100
	4	300 12000	300 12000	200	100

ML A2
ML E

APPENDIX 2

Dominant Climax Species Present in SCS Range Site Descriptions

Graminoids

Agro.	*Agropyron* spp.[1]
Agsm	*A. Smithii*
Agsp	*A. spicatum*
Agtr	*A. trachycaulum*
Andro.	*Andropogon* spp.
Anba	*A. barbinodis*
Ange	*A. gerardi*
Anha	*A. hallii*
Anli	*A. littoralis*
Ansc	*A. scoparius*
Avfa	*Avena fatua*
Bocu	*Bouteloua curtipendula*
Boer	*B. eriopoda*
Bugr	*B. gracilis*
Bohi	*B. hirsuta*
Brca	*Bromus carinatus*
Brmo	*B. mollis*
Brri	*B. rigidus*
Buda	*Buchloe dactyloides*
Caru	*Calamagrostis rubescens*
Calo	*Calamovilfa longifolia*
Carex	*Carex* spp.
Cafi	*C. folifolia*
Cage	*C. geyeri*
Cane	*C. nebraskensis*
Deca	*Deschampsia caespitosa*
Dist	*Distichlis stricta*
Elci	*Elymus cinereus*
Erin	*Eragrostis intermedia*
Feid	*Festuca idahoensis*
Feme	*F. megalura*
Fesc	*F. scabrella*
Hija	*Hilaria jamesii*
Himu	*H. mutica*
Junc.	*Juncus* spp.
Ledu	*Leptochloa dubia*
Muem	*Muhlenbergia emersleyi*
Mupo	*M. porteri*
Orhy	*Oryzopsis hymenoides*
Paob	*Panicum obtusum*
Pavi	*P. virgatum*
Pasp.	*Paspalum* spp.
Poa	*Poa* spp.
Pofe	*P. fendleriana*
Poju	*P. juncifolia*
Pone	*P. nevadensis*
Pose	*P. secunda*
Puai	*Puccinellia airoides*
Scbr	*Scleropogon brevifolius*
Sema	*Setaria macrostachya*
Sihy	*Sitanion hystrix*
Sonu	*Sorghastrum nutans*
Sppe	*Spartina pectinata*
Sporo.	*Sporobolus* spp.
Spai	*S. airoides*
Spas	*S. asper*
Spcr	*S. cryptandrus*
Spgi	*S. giganteus*
Spwr	*S. wrightii*
Stco	*Stipa comata*
Stth	*S. thurberiana*
Stvi	*S. viridula*
Trich.	*Trichloris* spp.

Forbs

Basa	*Balsamorhiza sagittata*
Erci	*Erodium cicutarium*
Eriog.	*Eriogonum* spp.
Lup.	*Lupinus* spp.
Opunt.	*Opuntia* spp.
Tri.	*Trifolium* spp.

Shrubs

Acacia	*Acacia* spp.
Agave	*Agave* spp.
Ararn	*Artemisia arbuscula* var. *nova*
Arfi	*A. filifolia*
Arri	*A. rigida*
Artr	*A. tridentata*
Artrv	*A. tridentata* ssp. *vaseyana*
Artrw	*A. tridentata* ssp. *wyomingensis*
Atca	*Atriplex canescens*
Atco	*A. confertifolia*
Atga	*A. gardneri*
Cepa	*Celtis pallida*
Coleo.	*Coleogyne* spp.
Eula	*Eurotia lanata*
Flce	*Flourensia cernua*
Krame.	*Krameria* spp.
Latr	*Larrea tridentata*
Pofr	*Potentilla fruticosa*
Rhtr	*Rhus trilobata*
Rosa	*Rosa* spp.
Save	*Sarcobatus vermiculatus*
Shar	*Shepherdia argentea*
Syal	*Symphoricarpos albus*
Syor	*S. oreophilus*
Yucca	*Yucca* spp.
Yuba	*Y. baccata*

Trees

Cepa	*Celtis pallida*
Jumo	*Juniperus monosperma*
Juos	*J. osteosperma*
Jusc	*J. scopulorum*
P–J	*Pinus edulis – Juniperus* spp.
Pied	*P. edulis*
Pipo	*P. ponderosa*
Prju	*Prosopis juliflora*
Prun.	*Prunus* spp.
Quer.	*Quercus* spp.
Qudo	*Q. douglasii*
Qulo	*Q. lobata*
Quma	*Q. marilandica*
Qust	*Q. stellata*
Quvi	*Q. virginiana*

[1]*The term "spp." designates that either multiple species of the same species of the same genera are present, or the species is unknown.*

Mitchell, John E., and James B. Pickens. An evaluation of herbage and browse production estimators used in the 1980 RPA assessment. USDA Forest Service Research Paper RM–259, 32 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Interdisciplinary team estimates of herbage/browse production used in the 1980 RPA Assessment were evaluated using three approaches. Estimates for nontimbered areas were mostly accurate; however, intrinsic relationships between forage production and productivity/condition classes were inconsistent. Production estimates for forested areas were more difficult to intrepret, in part because of insufficient independent data. Intrinsic relationships were also inconsistent.

Keywords: herbage/browse/forage production, RPA Assessment, interdisciplinary teams, intuitive models, range sites

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526

United States
Department of
Agriculture

Forest Service

**Rocky Mountain
Forest and Range
Experiment Station**

Fort Collins,
Colorado 80526

**Research Paper
RM-260**

Modeling Acreage Changes in Forest Ownerships and Cover Types in the Southeast

Ralph J. Alig

CLEMSON UNIVERSITY
JUL 16 1985
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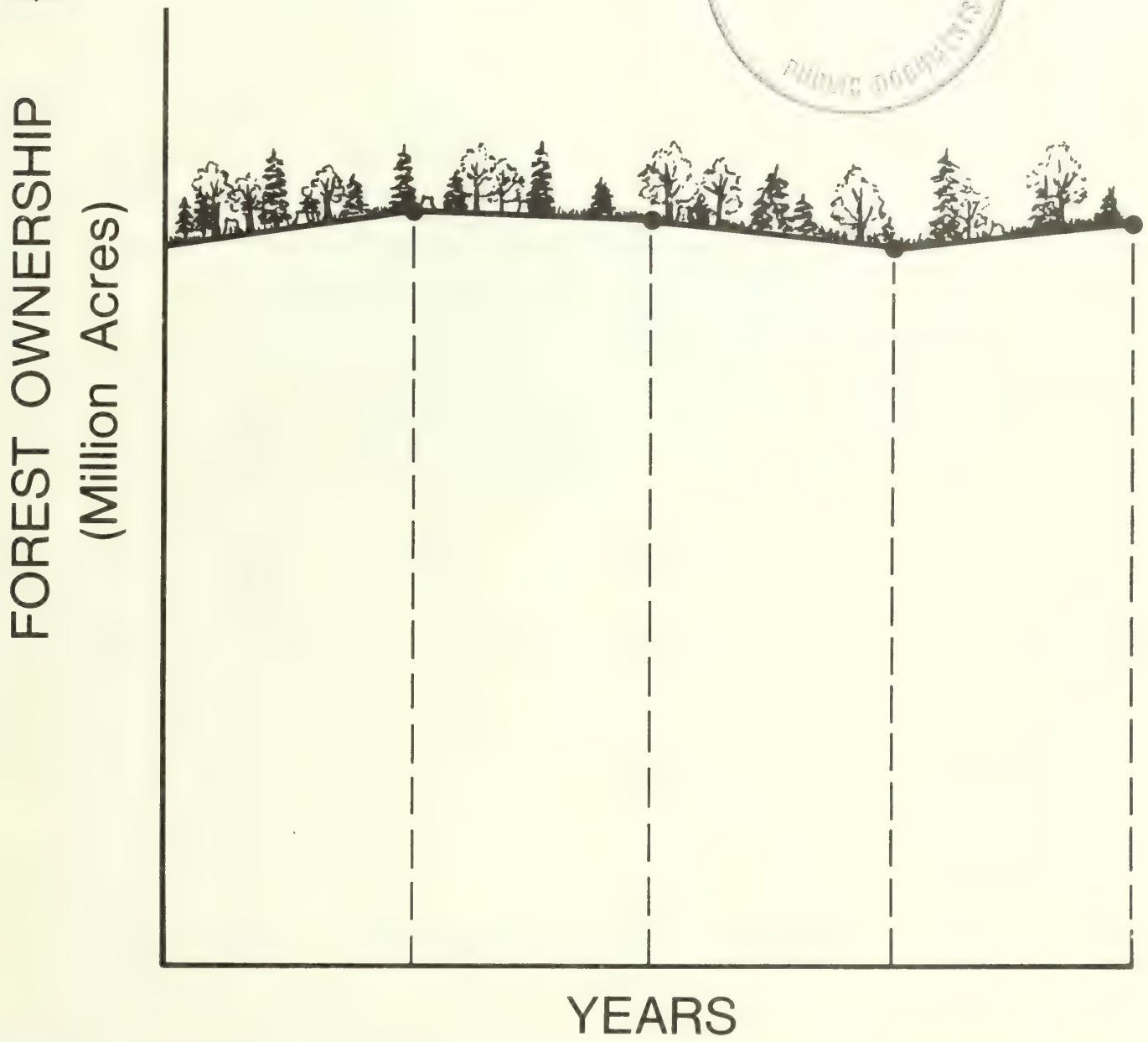

Acknowledgments

Special thanks to Herbert A. Knight, USDA Forest Service, Southeastern Forest Experiment Station, who provided data and reviewed study procedures and results; and to Darius M. Adams, Oregon State University; Robert Healy, Conservation Foundation; and Fred White, University of Georgia, for their assistance and advice.

USDA Forest Service
Research Paper RM–260

April 1985

Modeling Acreage Changes in Forest Ownerships and Cover Types in the Southeast

Ralph J. Alig, Research Forester
Rocky Mountain Forest and Range Experiment Station[1]

Abstract

A system based on economic criteria projects changes in acreages of six major land ownerships/uses by physiographic region in the Southeast, including three private forest ownership classes. Acreage changes for five major forest types, on each of the three forest ownerships, are projected using transition rates among forest types associated with the application of certain management practices. Changes in forest acreage, projected by decade to the year 2040, indicate a continued drop in farm forest acreage and natural pine acreage.

[1]*Headquarters is in Fort Collins, in cooperation with Colorado State University.*

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Modeling Acreage Changes in Forest Ownerships and Cover Types in the Southeast

Ralph J. Alig

Management Implications

Prospective changes in acreages for major land uses/ownerships and forest types are important considerations in the formulation of renewable resource policy. Competition among rural land uses is expected to be particularly intense over the next several decades in the Southeast because several sectors of the economy may expand production there. Changes in ownership distribution and in acreages of forest types can lead to substantial impacts on a variety of natural resources.

Population, personal income, and land commodity incomes are significant variables in land ownership/use equations. Changes in population and personal income levels have contributed to a decline in farm forest acreage and a corresponding increase in miscellaneous private forest acreage.

Projections with the system of land owner/use equations developed in this paper indicate a continued drop in farm forest acreage. Miscellaneous private forest acreage is projected to continue to increase. Projections of acreage changes for the five major forest types by ownership in each physiographic region indicate a substantial reduction in natural pine acreage. The probabilities of area changes in forest types were estimated from forest survey remeasurement data, and depend on application of certain management practices.

Because of the influence of external factors (e.g., population) on forest acreage trends, improved coordination of land use modeling for all sectors of the economy is needed. Also, forest acreage modeling needs to be integrated in an interregional framework with that for forest type transition, timber inventory projection, and harvest estimation.

Introduction

Projected acreage changes for land uses, ownerships, and forest types play an important role in both the analytical and policy aspects in the periodic assessments of long-range forest and range market trends required by the Forest and Rangeland Renewable Resources Planning Act of 1974. For example, acreage shifts influence both short-term timber supply and long-term timber investment behavior, and consequently, the supply of lumber and plywood. When acreage is removed from the timberland base, part of the associated inventory is marketed and contributes to current harvest (i.e., stumpage supply). However, loss of these acres reduces the aggregate growth potential of the timber resource. Supply may be lower than it would have been if these acres had been retained, depending in part on changes in timber investment in response to higher stumpage prices because of acreage reductions. The higher stumpage prices can drive up resource costs in a region, resulting in shifts in regional production of forest products (Alig et al. 1983). In addition, acreage shifts involving forestland impact both economic and ecological systems, including other natural resources (e.g., wildlife habitat) (Alig 1983).

Rural land use competition is expected to be particularly intense during the next several decades in the Southeast. Different sectors of the economy, including crop agriculture, pasture and range based agriculture, and forestry, may expand production there. In recent studies, more than 11 million acres of forest in the Southeast (15% of the timberland base) were identified as having high or medium potential for conversion to cropland (Dideriksen et al. 1977). The South had the largest population increase of all U.S. regions between 1950 and 1980; therefore, impacts of continued population expansion on the rural land base area are also important.

Forest acreage projections in previous timber supply assessments were based on opinions of regional experts, such as Wall's (1981) projection of commercial forest land acreage by region in the 1980 RPA Assessment (USDA Forest Service 1982). To estimate future commercial forest land, Wall subtracted the number of acres estimated to be withdrawn for uses of perceived higher economic (e.g., agriculture) or social value (e.g., wilderness) from the potential commercial forest land base. These projections then were used in estimating stumpage supply in the Timber Assessment Market Model (TAMM). Adams and Haynes (1980) recognized that the amount of forested acreage is not independent of the timber price projections made in TAMM, but concluded that the decisions involving the many possible uses of land are too complex for direct inclusion in TAMM.

One weakness of the expert opinion approach has been that the questions addressed are not empirically linked to objective and independently verifiable criteria (Sackman 1974). Sackman (1974) concluded that the technique is essentially unreliable and scientifically unvalidated. Armstrong (1978) was also critical of this type of approach.

Burnham (1973) used a Markov model to simulate land use changes over time in estimating future United States cropland availability. The finite Markov chain process employed probabilities of land use shifts based on movements between use groups over a historical time period. MacDonald et al. (1979) also applied a Markov chain model to project bottomland hardwood acreages in the Lower Mississippi alluvial plain to 1995.

Another weakness of expert opinion or Markov type approaches is that they do not allow a systematic analysis of the dynamic relationships among major economic variables and changes in forest acreage and ownership distribution. Projecting changes based on past land use trends does not identify the causes of these changes, therefore, the processes underlying land use shifts can not be quantified. The Markovian probabilities are aggregate measures of all influences acting on land use shifts. In addition, implicit assumptions, such as the stationarity assumption for land use transitions, may be unrealistic because of changing economic conditions.

When previous approaches are used, the effects of alternative policies on future area patterns can be examined only by means of very rough parametric shifts in land allocations; however, the relationship of these changes to the alternative policies of interest may not be clear. These approaches generally suggest that future land use patterns will be continuations of historic trends, despite the fact that different future economic and social conditions may be expected.

Other analytical approaches include the soil expectation value framework used by Vaux (1973) and Hyde (1980). These economic efficiency models can estimate long-term steady-state outcomes, but lack mechanisms for modeling the dynamics of changes in forest acreages. They also do not consider conversion of forestland to major competing uses (e.g., agriculture). Georgia Supply (GASPLY) (Montgomery et al. 1975, Robinson et al. 1978), another static economic model, does model conversions between forest and agriculture uses; however, it also lacks mechanisms for modeling adjustments over time that are needed for empirical testing.

The Center for Agricultural and Rural Development (CARD) model, developed to project changes in agricultural land use (English et al. 1982), projects conversion from forestland to cropland. The CARD model has estimated the conversion using the normative concept of least cost production to meet specified consumption levels. However, it has not considered land shifts to forestry (i.e., assumes returns to forestry are not positive). Because land use models, in general, have not projected all major land uses simultaneously, total land base constraints have not been explicitly addressed.

No regional projection models of changes in forest acreage have been developed that reflect historical relationships among ownership distribution, relative land product price trends, and other important land use determinants. One reason is that it is difficult to construct adequate time series of data for historical land use patterns. Classification criteria used to define timberland differ among major data sources. The most reliable series of forest acreage data consists of periodic estimates for survey regions within a state (Alig 1984a).

The limited success in projecting changes in land use may partially be the result of several combined characteristics of the market, owners, and analyses themselves. Imperfect market information, uncertainty, "noneconomic" goals, and lack of technical skills are examples of possible confounding market and owner-related factors. Analyzing the impact of changing government programs (e.g., USDA ERS 1983) on crop acreage has been a central problem in agricultural supply analysis since World War II (Houck et al. 1976). Government programs were often altered to reflect changing short-run views of economic conditions. An important analytical shortcoming may also be the inability to fully account for relevant returns, especially nonmonetary benefits, and costs accruing to a landowner from alternative land uses. This includes the influences of nontimber outputs on timberland management decisions, which have not been extensively tested (Binkley 1981).

The study reported here was designed to provide a modeling framework for projecting long-term changes in the acreages of the major land uses, forest ownerships, and forest types. A related paper (Alig 1984b) presents details on the estimation of the econometric equations that are used as a basis for the long-term projections of the acreages changes. This paper focuses on the projection methodology and the data used to support the projections.

Projection Methodology for Land Uses and Ownerships

Econometric equations that use economic, demographic, and other important variables were incorporated into a model, the Southeast Area Model (SAM), that projects acreages of the major land uses and forest ownerships in the Southeast. An overall schematic of the SAM system is presented in the Appendix. The development of the theory and estimation of the econometric models were described by Alig (1984b). The specified relationships for the six land owner/use classes are presented in table 1. The equations are based on land rent theory that suggests that the fraction of the land base devoted to a land use will be positively related to rent for that use relative to rents from competing uses.

The land use equations were estimated simultaneously using a seemingly unrelated regression approach, including the use of pooled cross-sectional and time series data. Data for the dependent variables, which represent the proportion of the land base occupied by a land use/owner, were collected by the USDA Forest Service, Forest Inventory and Analysis (FIA) unit at Asheville, N.C. Land use acreages for a state are estimated periodically in such surveys, with the entire Southeast covered approximately in 10-year cycles.

The estimated econometric equations are presented in tables 2, 3, and 4 for the Coastal Plain, Piedmont, and Mountain regions, respectively. The econometric results vary somewhat by region, but suggest that demographics and macroeconomics have important influences on land use changes in each physiographic region. The least satisfactory equations in terms of goodness of fit are the forest industry and pasture/range equations for the Coastal Plain.

Table 1.—Specified relationships for the six land owner/use classes.[1]

$$C = a_1 + b_1 Y_{F/C} + c_1 Y_{C/P} + d_1 UPOP + e_1 RPOP + f_1 Y_T$$
$$P = a_2 + b_2 Y_{F/P} + c_2 Y_{C/P} + d_2 UPOP + e_2 RPOP + f_2 Y_T$$
$$U = a_3 + d_3 UPOP + e_3 RPOP + f_3 Y_T$$
$$FA = a_4 + b_4 Y_{F/C} + c_4 Y_{F/P} + d_4 UPOP + e_4 RPOP + f_4 Y_T + g_4 G_s$$
$$FI = a_5 + b_5 R + c_5 Y_s + d_5 UPOP + e_5 RPOP + f_5 Y_T + h_5 S$$
$$MP = a_6 + b_6 I + d_6 UPOP + e_6 RPOP + f_6 Y_T + g_6 G_o + h_6 S$$

Where:

- C = Percentage of survey unit's land base occupied by crops
- P = Percentage of survey unit's land base occupied by pasture/range
- U = Percentage of survey unit's land base occupied by urban and other related uses
- FA = Percentage of survey unit's land base occupied by farm forestland
- FI = Percentage of survey unit's land base occupied by forest industry forestland
- MP = Percentage of survey unit's land base occupied by miscellaneous private forestland
- $a_i\ b_i\ c_i\ d_i\ e_i\ f_i\ g_i h_i$ = Parameters to be estimated ($i = 1,...,6$)
- $Y_{F/C}$ = Ratio of expected forestry to crop income per acre
- $Y_{C/P}$ = Ratio of expected crop to pasture/range income per acre
- $Y_{F/P}$ = Ratio of expected forestry to pasture/range income per acre
- $UPOP$ = Urban population
- $RPOP$ = Rural population
- Y_T = Real per capita income
- S = Expected southern pine stumpage income
- G_s = Tree planting expenditures under the Soil Bank program
- G_o = Tree planting expenditures under other government programs
- R = Proportion of forest industry softwood removals to total removals
- Y_s = Southern pine products income
- I = Inflation rate

[1]*Dummy variables to distinguish major geographic areas are not shown, but would be included in each equation.*

Table 2.—SURE econometric estimation results for the Coastal Plain Region.[1]

Variables	Crop	Pasture/ Range	Urban/ Other	Farm forest	Forest industry	Misc. private
Intercept	19.02*	9.27*	11.46*	37.30*	25.45*	5.12*
	(7.37)	(3.64)	(8.28)	(4.53)	(6.00)	(2.50)
Timber income				.69		
				(.25)		
Beef income		−1.37				
		(−1.73)				
Personal income	−1.11		6.28*	−19.61*		8.94*
	(−.45)		(4.59)	(−6.28)		(3.43)
Urban population	−5.37*		1.16*	−3.98*		2.00*
	(−6.02)		(2.02)	(−4.63)		(2.71)
Rural population					−3.49*	
					(−2.22)	
Wood products income					11.15*	
					(1.74)	
Industry removals (%)					6.69*	
					(2.92)	
Government forestry programs						1.91*
						(3.53)
Georgia dummy			−5.40*		−5.71*	
			(−4.37)		(−2.92)	
North Carolina dummy		−3.48*	−2.18			
		(−5.68)	(−1.77)			
South Carolina dummy		−2.78*			−7.33*	
		(−4.76)			(−4.03)	
Virginia dummy		−3.22*	−2.54	11.34*		
		(−4.00)	(−1.82)	(4.52)		
MAE[2]	4.89	1.30	2.62	3.68	5.05	2.83
Mean of dependent variable	22.58	3.25	13.59	28.44	15.72	16.43
Adjusted R^2	.54	.28	.53	.82	.32	.75
Sample size, n = 36						

[1]*Number in parentheses below coefficients are t-statistics.*
[2]*Mean absolute error.*
**Significantly different from zero at the 0.05 level.*

Table 3.—SURE econometric estimation results for the Piedmont Region.[1]

Variables	Crop	Pasture/ Range	Urban/ Other	Farm forest	Forest industry	Misc. private
Intercept	17.99*	5.28	4.87*	25.87*	6.66*	15.37*
	(5.76)	(1.09)	(4.13)	(3.52)	(10.95)	(4.17)
Beef income		1.27				
		(.87)				
Crop income	8.12*					
	(2.56)					
Timber income				9.11*		
				(4.45)		
Personal	−15.96*		6.04*	−23.15*		23.02*
income	(−7.87)		(5.31)	(−6.59)		(6.97)
Rural	−15.42*					21.91*
population	(−4.24)					(7.22)
Urban			1.25*	−6.34*	−1.87*	
population			(2.15)	(−7.62)	(−3.36)	
Inflation rate				−7.94*	6.31*	
				(−3.43)	(7.44)	
Government						1.07*
forestry programs						(1.75)
Georgia dummy				−5.76*		
				(−3.43)		
North Carolina	18.78*				−5.05*	−21.74*
dummy	(5.51)				(−5.28)	(−5.71)
South Carolina		−2.53*	3.33*	−14.64*		
dummy		(−2.05)	(4.25)	(−7.68)		
Virginia	−8.17*	4.75*			−3.35*	
dummy	(−3.48)	(4.04)			(−4.20)	
MAE[2]	2.45	2.55	1.97	3.49	1.71	4.34
Mean of dependent variable	19.45	10.18	9.96	33.15	6.69	20.57
Adjusted R^2	.76	.31	.73	.84	.60	.73
Sample size, n = 21						

Table 4.—SURE econometric estimation results for the Mountains Region.[1]

Variables	Crop	Pasture/ Range	Urban/ Other	Farm forest	Forest industry	Misc. private
Intercept	19.22*	23.51*	67.55*	−13.84	2.20	−27.72
	(18.64)	(5.79)	(17.46)	(−1.11)	(.77)	(−1.80)
Crop income	5.57*					
	(2.03)					
Beef income		−7.44*				
		(−5.74)				
Timber income				10.84*		1.89
				(3.01)		(.41)
Personal	−12.46*			−17.55*	−2.26	22.71*
income	(−8.88)			(−4.82)	(−1.45)	(4.37)
Urban		−4.29*	21.25*	−11.40*	−2.42*	−9.94*
population		(−3.17)	(11.21)	(−3.18)	(−2.05)	(−2.86)
Inflation rate					3.91*	
					(3.70)	
Government						2.29*
forestry programs						(4.06)
North Carolina	−4.30*		1.82			
dummy	(−5.66)		(1.89)			
Virginia		13.13*	−6.61*		−3.71*	−3.09
dummy		(15.85)	(−5.65)		(−4.74)	(−1.73)
MAE[2]	.82	1.15	1.91	3.45	1.24	3.32
Mean of dependent variable	9.70	14.71	24.50	24.98	3.59	22.51
Adjusted R^2	.89	.94	.87	.74	.56	.70
Sample size, n = 13						

[1]*Number in parentheses below coefficients are t-statistics.*
[2]*Mean absolute error.*
**Significantly different from zero at the 0.05 level.*

The models project use/ownership acreages by decade to the year 2040 (fig. 1), which corresponds with the current RPA planning horizon for which other variables of interest (e.g., timber removals) are projected in related studies. The major land uses are projected simultaneously, with a total land base limit imposed so that projections can not exceed a state's land area (Alig 1984a). Initial discrepancies between actual total land area and the area projections are apportioned by the model according to weights that correspond to the relative percentage of the land base occupied by a use/ ownership.

Projections of land use and ownership shifts require a variety of assumptions regarding prospective trends for a diverse set of variables that influence land base changes. Highly accurate predictions for important variables, such as long-run population and economic growth, are not possible. Instead, reasonable assumptions are made about future levels of these variables that are based on (1) historical trends, (2) developments that affect those trends, and (3) expectations regarding future changes.

Projections of population through the year 2000 by state, prepared by the Bureau of the Census (USDC Bureau of the Census 1983), were used for the baseline case. Population projections for years beyond 2000 were based on extrapolation of the Bureau of Census projections and expert opinion. Projected total population estimates were apportioned into rural and urban components, using the most recent Census proportions, by physiographic region within a state. Projected population estimates were distributed within the survey units in a state according to the most recent census estimates of distribution within a state. Total population is projected to increase in Florida by more than 145% over the projection period, and by more than 50% in several of the other southeastern states (fig. 2).

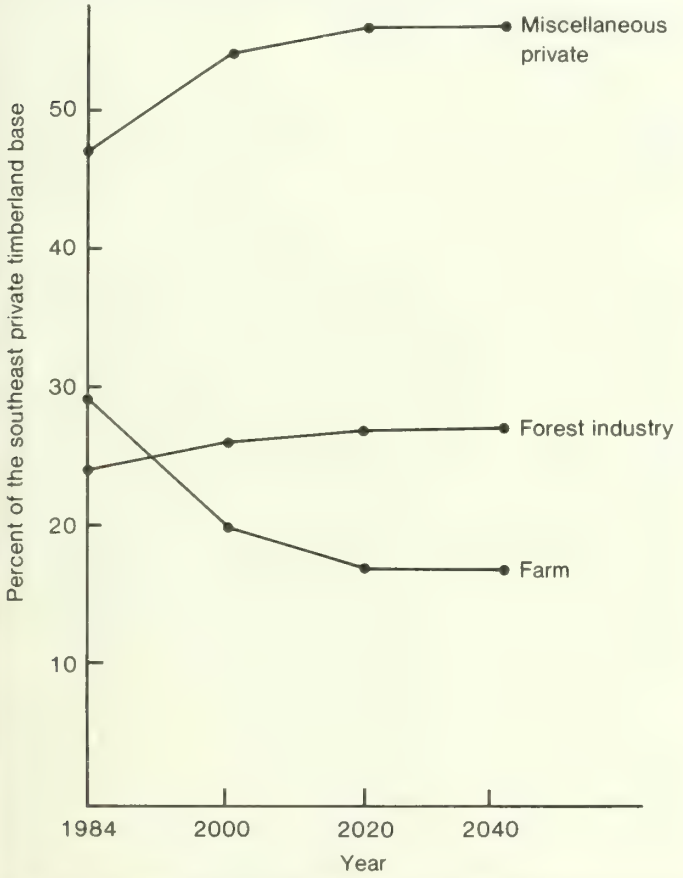

Figure 1. Projections of the distribution of private forest area by ownership in the Southeast.

Personal income projections were based on the national rate of change embodied in Gross National Product (GNP) projections to the year 2030 developed by the USDA Forest Service for RPA Assessment analyses.[2] The medium level of GNP rate of growth was used, which is based partly upon "medium" level projections of population and associated projections of labor force and productivity. The projected rate of economic growth results in a tripling of real per capita income by the end of the projection period (fig. 3). Historically, real per capita income has expanded approximately 2.5 times in the South since 1948 (USDC Office of Business Economics 1949). The fairly constant relationship between the levels of personal income and GNP for the past 50 years was assumed to continue through the projection period.

Projections of income per acre for crop and pasture/ range uses were based on agricultural price and productivity projections to the year 2030 in the Soil Conservation Service's RCA analysis (USDA 1981). The RCA price projections are based on the CARD/RCA modeling (English et al. 1982), and the ERS Report 435 (Lu et al. 1978) provided the guidance for the 1980 RCA assumptions regarding agricultural productivity. Constant real future crop prices were projected, with an annual productivity growth of 1.1% projected to the year 2000 and 0.9% annually thereafter. Constant real prices and no changes for productivity were assumed in projecting livestock incomes.

Timber incomes were projected based on an assumption of constant productivity and southern pine stumpage prices projected to the year 2030 by the Timber Assessment Market Model (Adams and Haynes 1980). Stumpage prices were adjusted by physiographic region and state using results from Hunter (1982). Projections of timber product prices and industry removal percentages also were based on TAMM projections. The TAMM projections, in turn, were based partly upon earlier area projections formulated from expert opinion (Wall 1981). However, the simultaneous determination each decade of area changes and changes in related economic parameters, such as timber prices, was outside the scope of this study.

Projected inflation rates were based on Wharton's baseline long-term forecast of price indices (Wharton 1983). Wharton's projections up to the year 2002 were extrapolated to the year 2040. The annual percentage changes projected for the price indexes ranged from approximately 2% to 5% over the projection period.

Current funding levels for government cost-share programs for tree planting were projected using annual

[2]*Personal communication with Adrian Haught, USDA Forest Service; RPA Staff; Washington, D.C. (November 1983).*

rates of real increase equal to 1%. Historically, real rates of funding increases have been greater than 3% annually (over some decades); but the projected values reflect slower annual increases because of anticipated reductions in such domestic programs.

Projected Area Changes

The projected area changes by forest ownership in figure 1 for the Southeast are similar across the three physiographic regions—Coastal Plain, Piedmont, and Mountains; only the regional projections are shown here. The largest acreage changes in the farm forest (5.7-million-acre reduction) and miscellaneous private (2.7-million-acre increase) classes are projected for the Coastal Plain. The largest acreage change for forest industry, a 1.4-million-acre increase, is projected for the Piedmont region.

The largest projected changes in Southeast forest acreage are for the farmer and miscellaneous private owner classes. Farm acreage is projected to continue to drop, with the projected 2040 value 45% lower than the 1984 acreage. In contrast, miscellaneous private acreage is projected to increase 11% by 2040. These divergent trends are similar to historical patterns. Most of the acreage changes in these two ownerships occur by the year 2000.

Projection Methodology for Forest Type Area

Long-range trends in projected natural resource supplies are sensitive to the forest type transition estimates used as input in timber inventory projection models

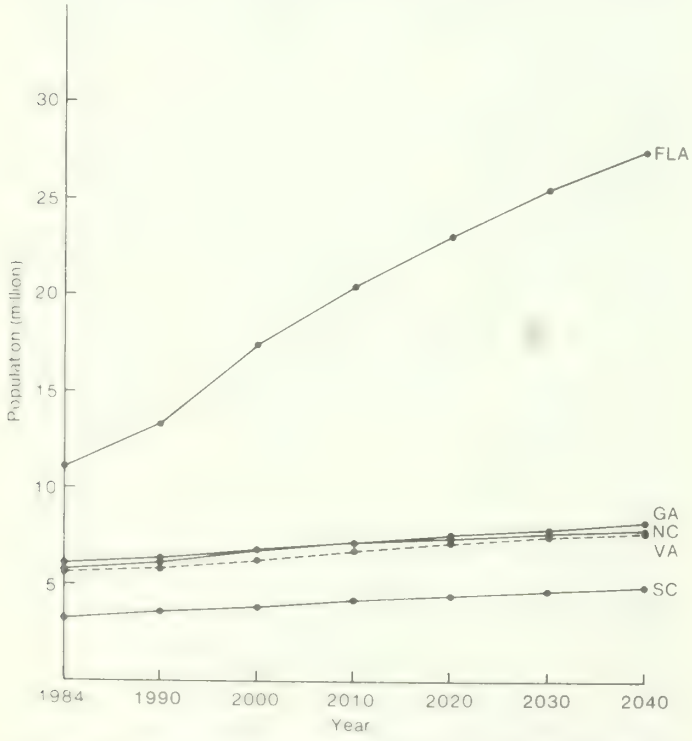

Figure 2. Projected population levels, by state for 1984 to 2040.

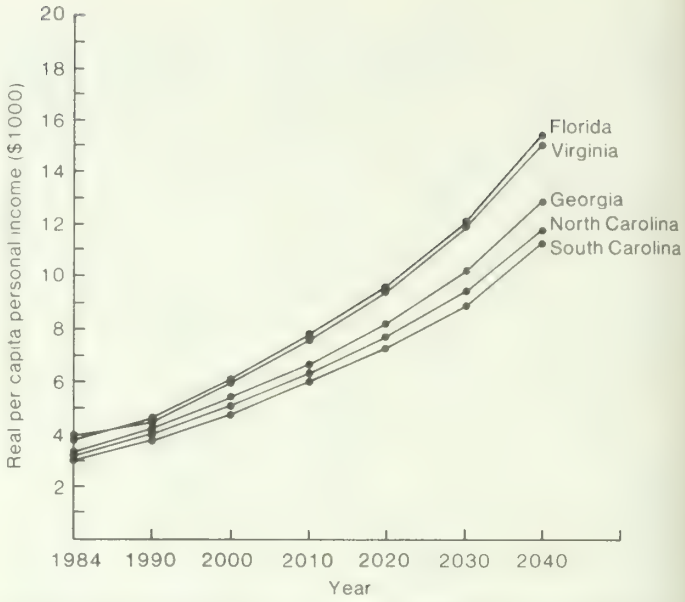

Figure 3. Projected levels of per capita personal income, by state for 1984 to 2040.

(Brooks 1984). The model used in this study to project forest type acreages is a preliminary attempt to address this question systematically. Research designed to improve upon this approach is described in a related study plan.[3]

Timber inventory projection models used in regional timber supply appraisals have based their simulation of future timberland management on three different approaches or assumptions (Alig et al. 1984): extrapolation of management implicit in measured stand growth rates, e.g., TRAS model (Alig et al. 1982), analysis of positive investment behavior, e.g., SPATS (Brooks 1984), and analysis of treatment opportunities, e.g., TRIM.[4] The SAM model can project forest type acreages to the year 2040 under any of these three assumptions regarding the application of land management practices.

The first option was used for the projections of forest type acreages in this study because of the availability of associated data. It simulates forest type transitions for three different categories of land management practices for which the USDA FIA survey group collects periodic data: (1) no management or disturbance, (2) final harvest, and (3) other miscellaneous management or disturbances. The simulations are based on historical rates of transition among major forest types. Three sets of input by owner and physiographic region are required: (1) original state or distribution of forest types, (2) probability of application of the three land management classes, and (3) conditional transition probability that a forest type will shift to a particular forest type in response to receiving one of the three types of manage-

[3] *Alig, Ralph J., James G. Wyant, and Herbert A. Knight. 1983b. Study plan: Analysis of forest type transition in the Southeast. USDA Forest Service Rocky Mountain Forest and Range Experiment Station. 47 p. Fort Collins, Colo.*

[4] *Tedder, P. L., J. P. Gourley, and R. N. Lamont. 1983. The timber resource inventory model (TRIM): A timber inventory projection model for national timber supply projections and policy analysis. Contract report to the USDA Forest Service, O-FRER staff. 155 p. Corvallis, Oreg.*

ment. The conditional forest type transition probabilities are multiplied by the management probabilities and the initial area[5] in a particular forest type on an ownership. The resultant area estimates are summed by owner, forest type, and physiographic region. The equation form is:

$$A_{i,j,t+1} = \sum_{j=1}^{5} \{ \sum_{k=1}^{3} \{ P(D_{k_{i,j,t}}) \times P(FT_{i,j,t+1}/D_{k_{i,j,t}}) \times A_{i,j,t} \} \}$$

Where:

$A_{i,j,t,}$ = Forest area in private ownership i and forest type j in decade t (i = 1,2,3; j = 1,...,5; t = 1...,7).

$P(D_{k_{i,j,t}})$ = Probability of a primary disturbance of type k on ownership i and forest type j in decade t (k = 1,2,3).

$P(FT_{i,j,t+1}/D_{k_{i,j,t}})$ = Probability of a unit area of timberland on ownership j in decade t + 1 being in forest type j in response to a primary disturbance of type k on that unit area in decade t.

The use of dynamic transition probabilities (i.e., a unique transition probability matrix for each time period) was precluded by the unavailability of data for developing appropriate adjustment mechanisms. The impact on forest type transitions of changes in management practices, such as increased timber investment levels or acceleration of private harvesting, can be simulated in sensitivity analyses by modifying the probability of management or the transition probabilities associated with certain management practices (or both). Incorporation of more detailed information on timber management practices is currently also precluded by lack of data.

The future distribution of forest types is projected in figure 4, using the transition probabilities for forest type by ownership given in table 5. These projections assume a similar future mix of land management practices will continue. An important land management concern is the lack of active forest regeneration efforts after harvest, in many cases on non-industrial private lands. Many acres shifted from pine to hardwood types, primarily after harvests that were not followed by pine regeneration efforts (Boyce and Knight 1979, 1980). As table 5 indicated, pine forests gradually convert to oak-pine, and then to hardwoods, if natural successional processes are not changed.

The probabilities for forest type transition in response to a type of land management, used in the projection of forest type distribution, are aggregate measures of all influences acting on forest development. These influences include human disturbances and natural succession forces (Alig and Wyant 1985). The investment behavior embodied in the forest type projections is not sensitive to changing relative prices for timber products. Modeling of timber investment activity has not kept pace with other recent advances in aggregate timber supply analysis (Alig et al. 1984).

[5]*Area adjustments by forest type for diversions from and reversions to the timberland base are estimated based on recent survey data.*

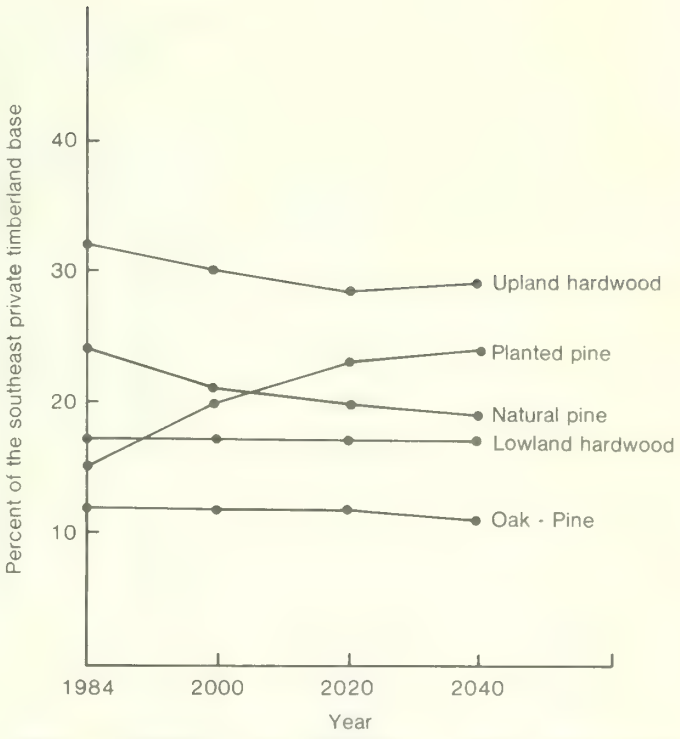

Figure 4. Projections of the distribution of private forest area by cover type in the Southeast.

Projected Area Changes

Historical rates of forest type transition by physiographic region were estimated from the most recent periodic FIA surveys (approximately one a decade) for Florida, Georgia, and South Carolina (table 5). Consistent transition information is only available for the most recent FIA surveys in this area. Therefore, the same transition rates were applied across all states, with distinct transition probabilities applied by physiographic region.

The projections of the distribution of private forest area by type in figure 4 indicate that the largest changes will occur in the southern pine types. Natural pine acreage is projected to decrease by more than 25% by year 2040. Planted pine acreage is projected to increase by more than 55% over the same period, mostly on forest industry lands. This shift in pine types results in little net change in southern pine acreage over the projection period.

Other Modeling Considerations

Constraints based on historical rates of transition were applied to the projections to preclude illogical or unreasonable trends in projected land use/ownership percentages. Region-wide land use trends are not quickly changed or reversed because of the slowly changing

Table 5.—Forest type transitions (in percentages) between the most recent two FIA surveys for Florida, Georgia, and South Carolina.

Forest type during earlier survey (Source)	Primary disturbance/ management	Probability of disturbance/ management	Probability of destination by forest type at latest survey				
			Natural southern pine	Planted southern pine	Oak-pine	Upland hardwood	Lowland hardwood
			Farm Ownerships				
Natural southern pine	None	29.4	90.8	0.0	6.7	2.0	0.5
	Harvest	23.8	39.1	9.3	17.5	25.6	8.5
	Miscellaneous	46.8	85.8	1.2	8.8	3.2	1.0
Planted southern pine	None	17.6	4.6	80.7	9.0	2.5	3.1
	Harvest	18.5	41.5	12.8	4.1	38.7	2.9
	Miscellaneous	63.9	5.8	91.1	1.1	1.2	0.7
Oak-pine	None	45.6	27.9	0.6	51.6	14.5	5.4
	Harvest	18.5	7.5	2.8	21.6	48.2	19.9
	Miscellaneous	35.9	23.6	2.7	43.1	24.4	6.2
Hardwood	None	54.9	1.7	0.0	8.2	40.7	49.4
	Harvest	13.9	3.3	1.8	4.3	42.9	47.7
	Miscellaneous	31.2	4.7	0.8	11.0	47.2	36.3
			Miscellaneous Private Ownerships				
Natural southern pine	None	29.4	92.9	0.5	4.7	1.7	0.2
	Harvest	43.8	34.2	18.6	19.9	22.5	4.7
	Miscellaneous	26.8	85.0	3.1	7.3	3.3	1.3
Planted southern pine	None	33.7	4.1	93.2	2.7	0.0	0.0
	Harvest	12.2	31.4	29.8	10.5	24.8	3.5
	Miscellaneous	54.1	4.2	92.9	2.1	0.8	0.0
Oak-pine	None	45.1	30.8	1.8	45.2	15.2	7.0
	Harvest	30.1	8.7	11.1	23.1	43.9	13.2
	Miscellaneous	24.8	28.1	2.8	36.8	28.0	4.3
Hardwood	None	58.3	1.6	0.1	8.6	43.3	46.4
	Harvest	17.6	3.4	8.1	13.4	43.7	31.4
	Miscellaneous	24.1	3.7	3.6	8.0	46.9	37.8
			Forest Industry Ownerships				
Natural southern pine	None	33.7	92.9	0.7	4.8	0.0	1.6
	Harvest	24.2	16.4	61.2	7.7	9.0	5.7
	Miscellaneous	42.1	72.8	16.6	6.0	3.0	1.6
Planted southern pine	None	29.2	1.8	94.6	2.1	0.8	0.7
	Harvest	16.9	13.7	57.7	9.5	16.9	2.2
	Miscellaneous	53.9	1.4	95.8	2.0	0.8	0.0
Oak-pine	None	47.7	21.6	6.7	46.1	12.0	13.6
	Harvest	17.7	5.6	25.5	17.4	34.2	17.3
	Miscellaneous	34.6	31.3	32.1	14.5	13.0	9.1
Hardwood	None	61.8	2.6	0.1	6.1	21.0	70.1
	Harvest	10.1	1.1	25.1	4.4	29.0	40.4
	Miscellaneous	28.1	4.7	25.1	7.4	19.2	43.6

macro forces at work. To reflect this, two types of constraints were imposed: (1) limits on percentage changes by decade for each land use/ownership, and (2) limits on the absolute percentage of land that may be occupied by a particular land use/ownership. These constraints were applied at the physiographic region level within each state, for each of the six major land uses/ ownerships.

Limits on changes in land use percentages by decade (table 6) were constructed from the author's analysis of historical trends and expert opinion.[6] Rapid changes in land use percentages are unlikely because of the capital limitations of owners, the inertial nature of land management, and the slowly changing trends in relative land product incomes.

The current extent of land use also was considered in setting the percentage limits. For example, forests generally have covered 60% to 80% of the Southeast; changes over a decade typically have been in the range of 2% to 15%. Parallel changes in pasture/range land use were 0.5% to 5% (pasture/range typically only occupies 2% to 15% of the land in a survey unit).

Limits on the upper and lower percentage ranges for each land use are presented in table 7. These also are

[6] *Personal communication with Herb Knight, USDA Forest Service, Southeastern Forest Experiment Station, Asheville, N.C. (November 1983).*

Table 6.—Bounds on rates of change (percentage of total land base) by decade in land use percentages.[1]

Physiographic region Land use/owner	Positive rates of change					Negative rates of change				
	Fla.	Ga.	N.C.	S.C.	Va.	Fla.	Ga.	N.C.	S.C.	Va.
Coastal Plain										
Farm forest	0.032	0.030	0.038	0.031	0.034	0.032	0.042	0.045	0.051	0.047
Forest industry forest	0.014	0.019	0.016	0.016	0.016	0.026	0.010	0.014	0.019	0.017
Miscellaneous private forest	0.027	0.038	0.038	0.038	0.038	0.031	0.033	0.036	0.030	0.031
Cropland	0.028	0.037	0.037	0.029	0.034	0.026	0.031	0.029	0.035	0.031
Pasture/range	0.026	0.028	0.024	0.019	0.018	0.026	0.026	0.021	0.019	0.018
Urban/other	0.029	0.026	0.029	0.026	0.026	0.013	0.013	0.013	0.013	0.013
Piedmont										
Farm forest	[1]	0.021	0.037	0.033	0.040	[1]	0.050	0.040	0.050	0.046
Forest industry forest	[1]	0.023	0.015	0.023	0.021	[1]	0.011	0.013	0.021	0.019
Miscellaneous private forest	[1]	0.042	0.041	0.046	0.040	[1]	0.026	0.030	0.036	0.034
Cropland	[1]	0.041	0.041	0.036	0.031	[1]	0.031	0.036	0.036	0.031
Pasture/range	[1]	0.028	0.030	0.038	0.031	[1]	0.030	0.026	0.028	0.030
Urban/other	[1]	0.030	0.038	0.032	0.027	[1]	0.013	0.017	0.016	0.016
Mountains										
Farm forest	[1]	0.023	0.039	[1]	0.036	[1]	0.048	0.043	[1]	0.043
Forest industry forest	[1]	0.020	0.019	[1]	0.019	[1]	0.017	0.026	[1]	0.013
Miscellaneous private forest	[1]	0.046	0.045	[1]	0.041	[1]	0.016	0.034	[1]	0.031
Cropland	[1]	0.044	0.038	[1]	0.032	[1]	0.030	0.033	[1]	0.032
Pasture/range	[1]	0.028	0.027	[1]	0.029	[1]	0.028	0.028	[1]	0.030
Urban/other	[1]	0.032	0.033	[1]	0.027	[1]	0.011	0.011	[1]	0.111

[1] *Indicates a nonexistent state-physiographic region combination.*

based on expert opinion and analysis of historical low and high percentages for each land use, by physiographic region within a state. All land use percentages were constrained to fall between 0% and 55%.

Use of these constraints relied heavily upon expert opinion in this first round of land use/ownership modeling, because the constraints reflected factors that have not been extensively researched. Sensitivity of the land use/ownerships projections to the imposition of the constraints on rates of change was tested by preparing a set of projections without the constraints. The projected acreages in the year 2040 for the two sets of projections differ by less than 10%, with the biggest changes in the crop and miscellaneous private forest categories. Therefore, while the constraints influenced the projections, they did not seriously affect projected results.

Other modeling considerations include the inability, because of data limitations, to differentiate among the several major types of owners combined in the diverse miscellaneous private class. In particular, corporate owners are an increasingly large part of this class. Also, existing data did not allow the leasing of nonindustrial lands to be handled meaningfully in this study.

Model Validation

Validation refers to evaluating a model's structure and behavior in comparison to the structure and behavior of the referent system to increase confidence in the ability of the model to provide reliable information or insights for analyzing policy issues. Validation addresses several questions pertaining to model application and utility: (1) whether the model is appropriate for its intended use(s); (2) whether the benefits of improving performance exceed the costs; (3) whether the model contributes to making "better" decisions; and (4) possibly how well the model performs compared to alternative models.[7] The general objective of the SAM research is to develop a model that can project long-term acreage changes for major land uses, ownerships, and forest types to support forest resources planning in RPA Assessments. The primary application is for the long-range evaluation of the impacts of a broad range of external forces (e.g., population growth) on land base shifts. The ultimate concern is with policy decision making and the value of related policy analyses, which is directly related to the accuracy of estimates of long-term changes on the land base. Mills and Flowers (1983) stress that an evaluation of the sensitivity of model outcomes to variations in input data and to variations in the completeness of model specification should be an integral part of any model building. If the model output is relatively unaffected by model refinement, those incremental costs are not justified.

[7] *McCarl, Bruce A., and A. Gene Nelson. 1983. Model validation: An overview with some emphasis on risk models. Paper presented at the annual meeting of Regional Research Project S-180, San Antonio, Texas, March 28-30, 1983.*

Table 7.—Upper and lower limits (percentage of the total land base) on occupation of the land base by major uses/ownerships.[1]

Physiographic region Land use/owner	Lower limits					Upper limits				
	Fla.	Ga.	N.C.	S.C.	Va.	Fla.	Ga.	N.C.	S.C.	Va.
Coastal Plain										
Farm forest	0.022	0.085	0.165	0.102	0.123	0.193	0.323	0.360	0.290	0.327
Forest industry forest	0.175	0.072	0.087	0.098	0.100	0.410	0.300	0.210	0.210	0.208
Miscellaneous private forest	0.165	0.095	0.115	0.131	0.124	0.417	0.295	0.340	0.325	0.319
Cropland	0.058	0.125	0.188	0.165	0.141	0.217	0.361	0.368	0.295	0.267
Pasture/range	0.023	0.021	0.011	0.015	0.016	0.182	0.168	0.085	0.086	0.076
Urban/other	0.092	0.035	0.081	0.111	0.080	0.285	0.207	0.210	0.223	0.234
Piedmont										
Farm forest	'	0.065	0.175	0.115	0.165	'	0.196	0.387	0.296	0.389
Forest industry forest	'	0.060	0.011	0.070	0.052	'	0.240	0.092	0.167	0.168
Miscellaneous private forest	'	0.195	0.145	0.187	0.147	'	0.520	0.347	0.382	0.358
Cropland	'	0.074	0.138	0.078	0.086	'	0.283	0.385	0.356	0.237
Pasture/range	'	0.056	0.031	0.038	0.078	'	0.185	0.136	0.178	0.219
Urban/other	'	0.059	0.098	0.091	0.091	'	0.220	0.206	0.242	0.205
Mountains										
Farm forest	'	0.050	0.095	'	0.084	'	0.190	0.281	'	0.285
Forest industry forest	'	0.038	0.015	'	0.011	'	0.140	0.105	'	0.096
Miscellaneous private forest	'	0.210	0.220	'	0.055	'	0.492	0.435	'	0.398
Cropland	'	0.048	0.036	'	0.039	'	0.187	0.169	'	0.186
Pasture/range	'	0.043	0.041	'	0.126	'	0.177	0.179	'	0.274
Urban/other	'	0.190	0.200	'	0.160	'	0.376	0.402	'	0.386

[1]*Indicates a nonexistent state-physiographic region combination.*

Validation exercises can vary widely, including comparison of model solution vectors with corresponding real world vectors. In a practical sense, validation is very difficult for long-range forestry-based models where outcome sets for comparative purposes are not available. Therefore, a frequently used approach to validation involves evaluating the goodness of fit of model simulations over historical periods (Kost 1980). Ideally, to evaluate predictive ability, several observations would be excluded from use in parameter estimation and used to evaluate the forecasting ability of the model. However, because of the limited number of available observations, it was necessary to use all the observations in this study for parameter estimation. Survey estimates of land use acreages were only made periodically for each state, which greatly limits validation that is based on data sets that are separate from those used in estimation.

Because unexpected future events cannot all be provided for in a model, researchers have proposed using model predictions for historical periods to examine a model's predictive ability (Salathe et al. 1982). Measures of a model's ability to replicate history include the traditional method of evaluating the accuracy of such models by the use of summary statistics, such as t-scores, F-tests, and R^2's statistics (Larson 1983). These statistics represent the type of information generally provided in articles dealing with evaluation of model performance. Other validation statistics also have been proposed to determine the predictive adequacy of econometric models (Pindyck and Rubinfeld 1976). The most widely used include: the percent root-mean-square (RMS) error, Theil's inequality (U) statistics, and the correlation coefficient. The root-mean-square (RMS) percentage error is defined as:

$$\text{Percent RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{\hat{Y}_{it} - Y_{it}}{Y_{it}}\right)^2}$$

Theil's inequality (U) statistic is defined as:

$$U = \frac{\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{\hat{Y}_{it} - Y_{it}}{Y_{it}}\right)^2}}{\sqrt{\frac{1}{N}\sum_{n=1}^{N}\hat{Y}_{it}^2} + \sqrt{\frac{1}{N}\sum_{n=1}^{N}Y_{it}^2}}$$

The coefficient of multiple determination (R^2) is defined as:

$$R^2 = \frac{\sum_{n=1}^{N} (\hat{Y}_{it} - \bar{Y})^2}{\sum_{n=1}^{N} (Y_{it} - \bar{Y})^2}$$

Where

- N = Number of sample observations for the dependent variable
- $\hat{Y}_{it}$ = Simulated level of the dependent variable for survey unit i at time period t
- Y_{it} = Actual level of the dependent variable for survey unit i at time period t
- $\bar{Y}$ = Mean level of the dependent variable over the survey units and time periods.

Performance of the Land Use Acreage Model

The SAM system was validated over the 1947–1983 period for which historical data was available. Model errors for the historical period stemmed from the inability of the SAM equations to exactly predict area changes for land uses/ownerships in any particular year. Table 8 presents the validation statistics computed for the land use equations in the SAM system. Overall, the equations appear to predict with reasonable accuracy. The farm/forest equations had the highest explanatory power of all equations in the Coastal Plain and Piedmont regions. In contrast, the pasture/range and forest industry equations had noticeably lower associated measures of predictive performance for those regions.

The goodness of fit of the forest acreage equations was similar across regions, except for the forest industry equations. The highest R^2's and lowest prediction errors for the nonforest land uses were associated with the Mountain equations. The R^2's for the Piedmont equations also were generally high, except for the pasture/range equation. For the Coastal Plain, the equations for forest industry and pasture/range were the least satisfactory. Alig (1984a) provided a detailed discussion of these differences and possible causes.

For example purposes, the predicted and actual values over the sample period for the farm forest ownership is plotted in figure 5 by physiographic region. The survey cycles represented on the horizontal axis refer to FIA remeasurement periods. The surveys for the five states were added at those four points in time to provide a basis for evaluating the historical simulations.

The predicted trends for the farm forest ownership approximated the actual trends closely. The predicted forest industry trends did not follow the actual trends as closely, especially in the Piedmont and Coastal Plain. The miscellaneous private forest equations closely tracked the actual trends, except for underestimating the Survey Cycle 3 level in the Piedmont region. This deviation is the converse of the overestimated Piedmont dip for the farm ownership during the same period.

Sensitivity analyses also were conducted to investigate the robustness of the SAM modeling system. As discussed by Alig (1984a), the long-term projections of acreage changes were not very sensitive to 30% changes (by decade) in assumptions pertaining to the major independent variables (e.g., urban population). The 30% change was selected to represent a realistic margin of error for the projections of major independent variables. Three factors may have contributed to the in-

Table 8.—Validation statistics for the SAM system, 1947–1983.

Physiographic region Land use/owner	Percent root-mean square (RMS) error	Theil U_2 statistic	Multiple correlation coefficient (R^2)
Coastal Plain			
Crop	35.2	.12	.57
Pasture/range	64.7	.22	.36
Urban/other	34.1	.11	.59
Farm forest	21.4	.08	.84
Forest industry forest	87.3	.18	.42
Misc. private forest	159.9	.10	.77
Piedmont			
Crop	17.2	.07	.82
Pasture/range	30.0	.14	.41
Urban/other	27.9	.11	.77
Farm forest	17.0	.06	.89
Forest industry forest	53.3	.14	.68
Misc. private forest	71.1	.11	.79
Mountains			
Crop	10.4	.05	.92
Pasture/range	12.6	.05	.96
Urban/other	9.8	.04	.91
Farm forest	25.1	.08	.80
Forest industry forest	86.8	.16	.71
Misc. private forest	31.4	.08	.83

sensitivity of the projections to input parameters: (1) the logarithmic functional forms of the land use relationships, (2) the small size of the incremental change relative to projected levels of change for the major independent variables, and (3) the constraints placed on the land use changes to preclude changes that would deviate significantly from historical trends.

The interaction of the three factors make it difficult to determine the relative importance of each. However, the latter two factors are thought to have the largest influences. For example, one of the major independent variables, population, is projected to increase by more than 145% in Florida and by more than 50% in several other states over the projection period. These are large changes relative to the incremental 30% increase. In addition, upper level constraints on rates of land use change in some cases further lessen the impact of increasing population levels. However, as discussed earlier, the constraints are not overriding in their effect, but may contribute to the influence of the other factors.

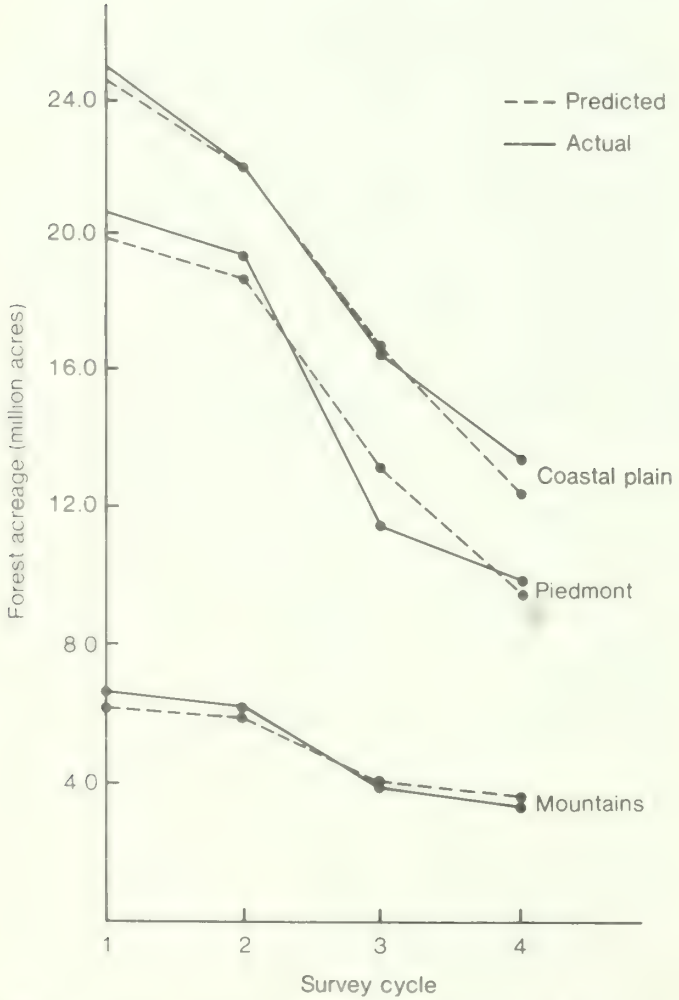

Figure 5. Actual and predicted changes in farm forest acreage by physiographic region.

Conclusions

Changes in population and personal income levels have contributed to a decline in farm forest acreage and a corresponding increase in miscellaneous private forest acreage. Projected changes in the acreages of forest ownerships with the SAM model, which is based on econometric equations, indicate a continued drop in farm forest acreage and an increase in miscellaneous private forest acreage. Projections of acreage changes for the five major forest types by ownership in each physiographic region point to a substantial reduction in natural pine acreage. These projections are based on application of certain management practices.

Research is needed to improve the efficiency of linking forest acreage estimation more strongly to forest type transition, timber inventory projection, harvest, and investment modeling in aggregate timber supply studies (Alig et al. 1984). Forest acreage projections support timber inventory projection modeling, and as a result the modeling of regional stumpage prices, number of acres devoted to forestry, and the timber management schemes are interrelated. This suggests that a simultaneous solution network or feedback loops are needed, which may be a long-term venture.

Further research also could include different data pooling techniques or examination of forest acreage trends on a less aggregated basis, possibly by state in order to isolate key factors underlying subregional forestland ownership strategies. Unavailability of data may preclude analyses at the state level (i.e., degrees of freedom problem), but at a minimum, aggregate studies can be augmented with descriptive studies at lower levels. One possible improvement, dependent on data availability, is the direct estimation of factors influencing changes in specific forest type acreages.

Attempts to validate long-term land use models have centered on methods of evaluating the goodness-of-fit of model simulations over historical periods. However, this is a subjective process that must consider possible future structural changes, and which involves using both economic and statistical criteria. Building confidence in the plausibility of the projections depends to some degree on logical extrapolations of empirical evidence, which is often limited in its extent and quality. Conventional statistical measures of uncertainty can only provide the basis for establishing an upper bound on the accuracy of projections. Validation in part rests on judgments based on historical data and perceptions formed by experiences related to the relationship of past to future populations under study. Although no definitive conclusions based on statistical theory can be drawn from this analysis, the model appears to be reasonable. As a proxy for reality, a model's behavior is evaluated to provide insight into analyzing economic issues. A more practical test of validity is to use the SAM model in an actual forecasting environment, with attention given to ranges of forecasts and the robustness of the model.

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Appendix

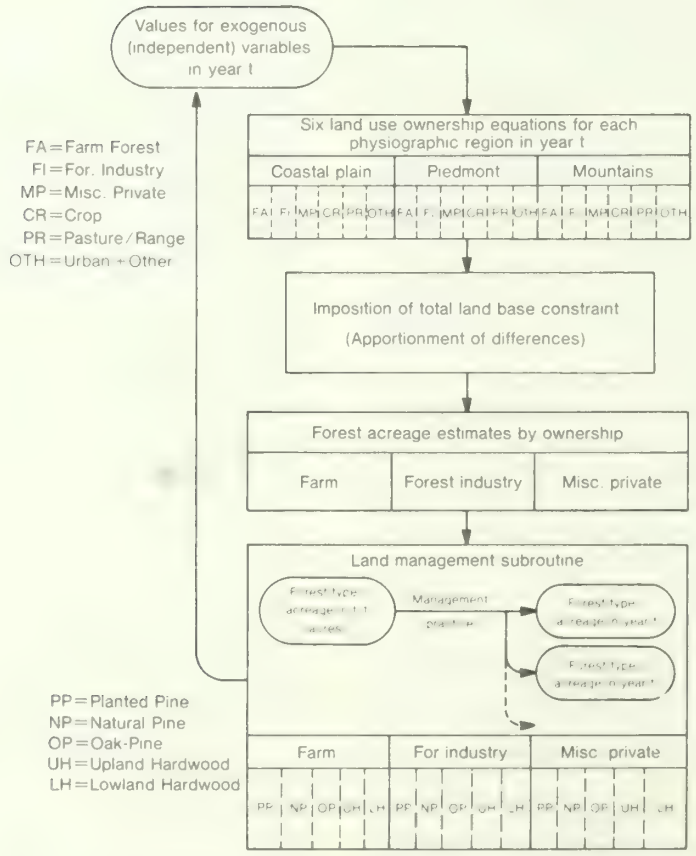

Figure 1A. Overall schematic of the Southeast Area Model.

GPO 846-603

Alig, Ralph J. 1984. Modeling acreage changes in forest ownerships and cover types in the Southeast. USDA Forest Service Research Paper RM-260, 14 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

A system based on economic criteria projects change in acreages of six major land ownerships/uses by physiographic region in the Southeast, including three private forest ownership classes. Acreage changes for five major forest types, on each of the three forest ownerships, are projected using transition rates among forest types associated with the application of certain management practices. Changes in forest acreage, projected by decade to the year 2040, indicate a continued drop in farm forest acreage and natural pine acreage.

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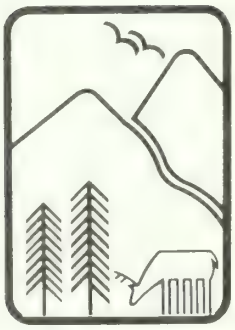

Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526

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